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Comparison of Fossil and Wood Fuels

Battelle Columbus Labs.

Prepared For
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March 1976

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16. ABSTRACT

The report gives results of a preliminary assessment, comparing the use of wood as a fuel for a commercial electric power plant in Vermont, with that of clean fossil fuels or fossil fuels with suitable polluation control technology. For the study, wood fuel was derived from forest surplus; i.e., the tops and branches of trees cut for commercial purposes, cull or noncommercial trees, and waste from forest products industries. The comparison considered boiler technology, pollutant emissions, control technology, energy balance, environmental/ecological impact, and cost. Conclusions included: the use of forest surplus and waste wood is technically feasible, pollutant emissions are controllable, net energy balances are favorable, the preliminary estimated cost is competitive, with proper forest management, there is potentially a net benefit to the ecology of Vermont's forest ecosystems, wood is a renewable resource, and a demonstration is recommended to advance the concept toward commercial application. Because wood is a competitive fuel, a cursory study was made, showing the concept to be applicable to other regions of the country for incremental electric power generation capacity.

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COMPARISON OF FOSSIL AND WOOD FUELS

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Prepared for

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ABSTRACT

A preliminary assessment was conducted of the use of wood as a fuel for a commercial electric power plant as compared with the use of clean fossil fuels, or fossil fuels with suitable pollution control technology. In the context of this study, wood fuel is to be derived from forest surplus, i.e., the tops and branches of trees,cut for commercial purposes, and the cull or noncommercial trees, and from waste from forest products industries. Wood was compared with alternative fuels with respect to boiler technology, pollutant emissions, control technology, energy balance, environmental-ecological impact, and cost. The general conclusions are as follows:

- The use of forest surplus and waste wood is technically feasible .
- Pollutant emissions are controllable.
- Net energy balances are favorable.
- The preliminary estimated cost is competitive.
- With proper forest management, there is potentially a net benefit to the ecology of Vermont's forest ecosystems .
- Wood is a renewable resource.
- Therefore, a demonstration to advance the concept toward commercial application is recommended.

In view of the fact that wood is a competitive fuel, a cursory study was made which showed the concept to be applicable to other regions of the country for incremental electric power generation capacity.

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CONVERSION OF UNITS

Some English units which are still in common use are employed in this report. The following table lists the factors to be used to convert English units to metric units.

Multiply English Unit	by Conversion	To Obtain Metric Unit
acres	0.405	hectares
acre-feet	1233.5	cubic meters
barrel, oil	158.97	liters
British Thermal Unit	0.252	kilogram-calories
British Thermal Unit/pound	0.555	kilogram calories/kilogram
cubic feet/minute	0.028	cubic meters/minute
cubic feet/second	1.7	cubic meters/minute
cubic feet	0.028	cubic meters
cubic feet	28.32	liters
cubic inches	16.39	cubic centimeters
degree Fahrenheit	0.555(°F-32)[a]	degree Centigrade
feet	0.3048	meters
gallon	3.785	liters
gallon/minute	0.0631	liters/second
horsepower	0.7457	kilowatts
inches	2.54	centimeters
inches of mercury	0.03342	atmospheres
pounds	0.454	kilograms
million gallons/day	3785	cubic meters/day
mile	1.609	kilometer
pound/square inch (gauge)	(0.06805 psig+1)[a]	atmospheres (absolute)
square feet	0.0929	square meters
square inches	6.452	square centimeters
tons (short)	0.907	metric tons (1000 kilograms)
yard	0.9144	meters

(a) Actual conversion, not a multiplier.

CONCLUSIONS

The use of forest surplus and waste wood as a fuel for an electric power generating station is technically feasible. Between 1965 and March of 1975, 230 boilers with the capacity to burn wood as the primary fuel or as an alternative fuel were sold in the United States.

The use of waste wood to fuel boilers is an environmentally acceptable method of power generation. Control technology for the collection of particulates is available. Total air emissions for wood-fueled systems are significantly less than acceptable alternative fuels such as physically-cleaned coal or low-sulfur Western coal.

Energy consumptions for recovery or procurement, for processing, and for transportation of fuel are lower for green wood than for all other alternatives except low-sulfur Western coal and imported oil.

The estimated cost of wood chips is competitive with the cost of all alternative fuels. The estimated cost of electricity for a wood-fueled plant is less than the costs estimated for electricity generated by the use of alternative fuels. These costs are based on preliminary analysis only.

With sound forest management practice, the use of forest surplus as fuel can be of benefit to the overall forest ecosystem. The effect of nutrient removal through surplus wood harvest is not completely known at this time. Available data are site specific and are difficult to project to other sites.

The concept of using surplus wood as fuel appears to be applicable to other regions of the country as well. Conservative estimates of surplus and waste forest biomass show an availability equal to 77 to 103 percent of the combined oil and gas consumption by utilities in the South Atlantic, Mountain, and Pacific regions.

There are no apparent reasons why the Milton Plant cannot be adapted to burn wood chips. However, the physical arrangement of the boilers is not preferred for burning such fuel. The deficiencies and countermeasures which may overcome them are discussed in the report.

INTRODUCTION

Background

The Green Mountain Power Corporation (GMPC) of Burlington, Vermont, is planning the addition of 50 MW of electric power generation capacity to their system. In view of the sharply higher costs of fossil fuels, the company is evaluating the feasibility of fueling the new plant with wood. The GMPC concept is to utilize forest surplus and the residuals from the forest products industries as the source of the wood fuel. This concept is distinctly different from the energy plantation concept, in which selected species are grown for the sole purpose of converting the resulting biomass to energy. The GMPC plan includes four principal sources of surplus or waste wood.

(1) Commercial timber harvest. In conjunction with a commercial timber cut, the tops, branches, and leaves removed from merchantable logs would be chipped, blown into a van, and transported to the power plant. During the same operation, the noncommercial trees would be cut and the entire tree chipped.

(2) Stand improvement cutting. Removal of culls from a timber stand improves the growing conditions for the remaining commercial stock in the same way that weeding is beneficial to a vegetable garden. Nevertheless, the practice is underutilized in Vermont, largely because of short-term economic considerations. A market for wood chips obtained from a stand improvement cut should provide wood lot owners an incentive to employ this beneficial forest management practice.

(3) Ecological cutting. Selected cutting on State and Federal forest lands designed to improve wildlife conditions could be an additional source of surplus wood. Again, a market for wood chips would allow government forest managers to expand the use of this technique beyond existing budgetary limitations.

(4) Forest products industries waste. The waste from sawmills and other forest products industries could be used to supplement other sources of wood as fuel for a power plant. The practice would benefit those industries by providing an outlet for otherwise waste material.

Burning wood under a boiler is not a new concept. There were 230 boilers with capability to burn wood, either as the primary fuel or as an alternate fuel, sold in this country between 1965 and March 1975. The technology is available and vendors are able to supply equipment designed to burn wood. Preliminary analysis by GMPC personnel showed that the quantity of surplus wood in Vermont greatly exceeds the requirements for a 50-MW plant. The major uncertainties in the concept lie in the logistics and the economics of the procurement of woodchips for fuel. In order to obtain better understanding in these areas of uncertainty, GMPC has submitted a proposal to the United States Environmental Protection Agency requesting funds to conduct a demonstration program. GMPC proposes to modify an existing 4 MW power plant located at Milton, Vermont, to receive and burn wood fuel and to operate this plant for a period of two years. During this time the critical factors in establishing a steady supply of wood fuel will be investigated by letting various types of contracts for wood chips. Other important elements of the proposed demonstration include evaluation of the burning characteristics of wood fuel, measurement of emissions, investigation of the ecological consequences of the proposed wood procurement techniques, and definition of proper forest management practices with respect to wood fuel procurement which will assure maximum benefit to Vermont's forest lands.

As an element in the evaluation of this proposal, the EPA awarded a contract to Battelle's Columbus Laboratories to conduct an independent assessment of the concept of using forest surplus and wood waste as a boiler fuel.

Objectives

The objectives of the study were as follows:

- To evaluate wood as a fuel for a 50-MW power plant in Central Vermont as compared with alternative fuels, which included: low-sulfur coal, physically cleaned coal, high-sulfur coal burned with stack gas scrubbing, and low sulfur fuel oil.
- To make a cursory study of the applicability of the concept to other areas of the country and to other sized power plants.
- To survey the Milton plant and assess the modifications required to satisfactorily receive and fire wood fuel, and to estimate the costs for all wood-handling, boiler-firing, and pollution-control modifications.

After an initial visit to the Milton site, concern about the stack height prompted the addition of a further objective, namely:

- To make a preliminary evaluation of the probable impact of burning wood at the Milton plant on the air quality in this vicinity; and, to estimate the usefulness of increasing the height of the stack.

Approach

The evaluation of the use of wood as a power-plant fuel as compared with alternative fuels was addressed with respect to five areas:

- Boiler technology
- Pollutant emissions and control technology
- Energy requirements
- Environmental-Ecological impact of wood procurement
- Comparative costs.

The methodology employed and the results obtained in each of these areas are described in separate chapters of this report.

Evaluation of Equivalent Fuel Costs

It is instructive to consider, at the outset, the monetary value of wood as a fuel as compared with alternative fuels. The value of wood depends upon its heating value and its moisture content. These properties vary widely. Although numbers may be assumed and equivalent values determined, it is important to know the sensitivity of the equivalent value to changes in heating value and moisture content. Such information is presented in Figure 1 for comparing the value of wood as a fuel for steam production with the cost of coal, and Figure 2 for comparing wood with the cost of residual oil.* Equivalent values are shown for two different heating values of dry wood: 8,500 Btu/dry pound, a medium value; and 7,000 Btu/dry pound, a relatively low value. The sensitivity of the equivalent value of wood to changes in moisture content also is displayed in Figures 1 and 2. Values for moisture content (wet basis) of 5 percent, 25 percent, and 50 percent were chosen. The presence of moisture affects the equivalent value of wood in two ways. The moisture adds to the weight of the wood which results in a proportionate decrease in the heating value "as received", as shown in the following tabulation:

Moisture Content Percent (wet basis)	Heating Value, Btu/lb	
	Medium	Low
0 (bone dry)	8,500	7,000
5	8,075	6,650
25	6,375	5,250
50	4,250	3,500

The second impact of moisture in the wood arises from the fact that part of the energy released as the wood burns is expended in vaporizing the water contained in the wood. This energy is lost and, as a result, the

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* These comparisons assume a value equivalency which is only a function of the fuel heating value and boiler efficiency. The relative costs of firing coal, oil, and wood are not included in these comparisons.

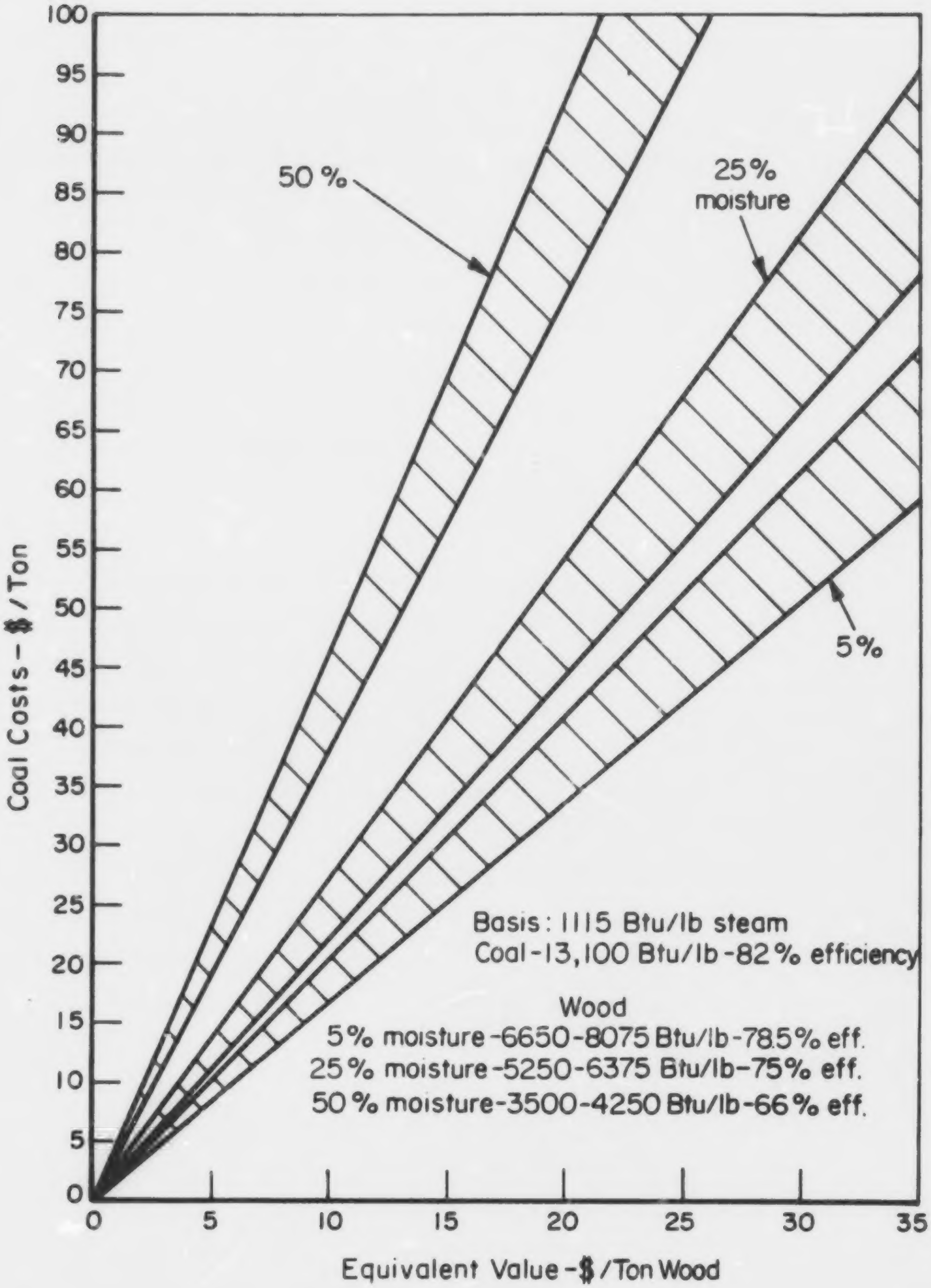

FIGURE 1. EQUIVALENT VALUE OF COAL AND WOOD
AT 5, 25, AND 50 PERCENT MOISTURE

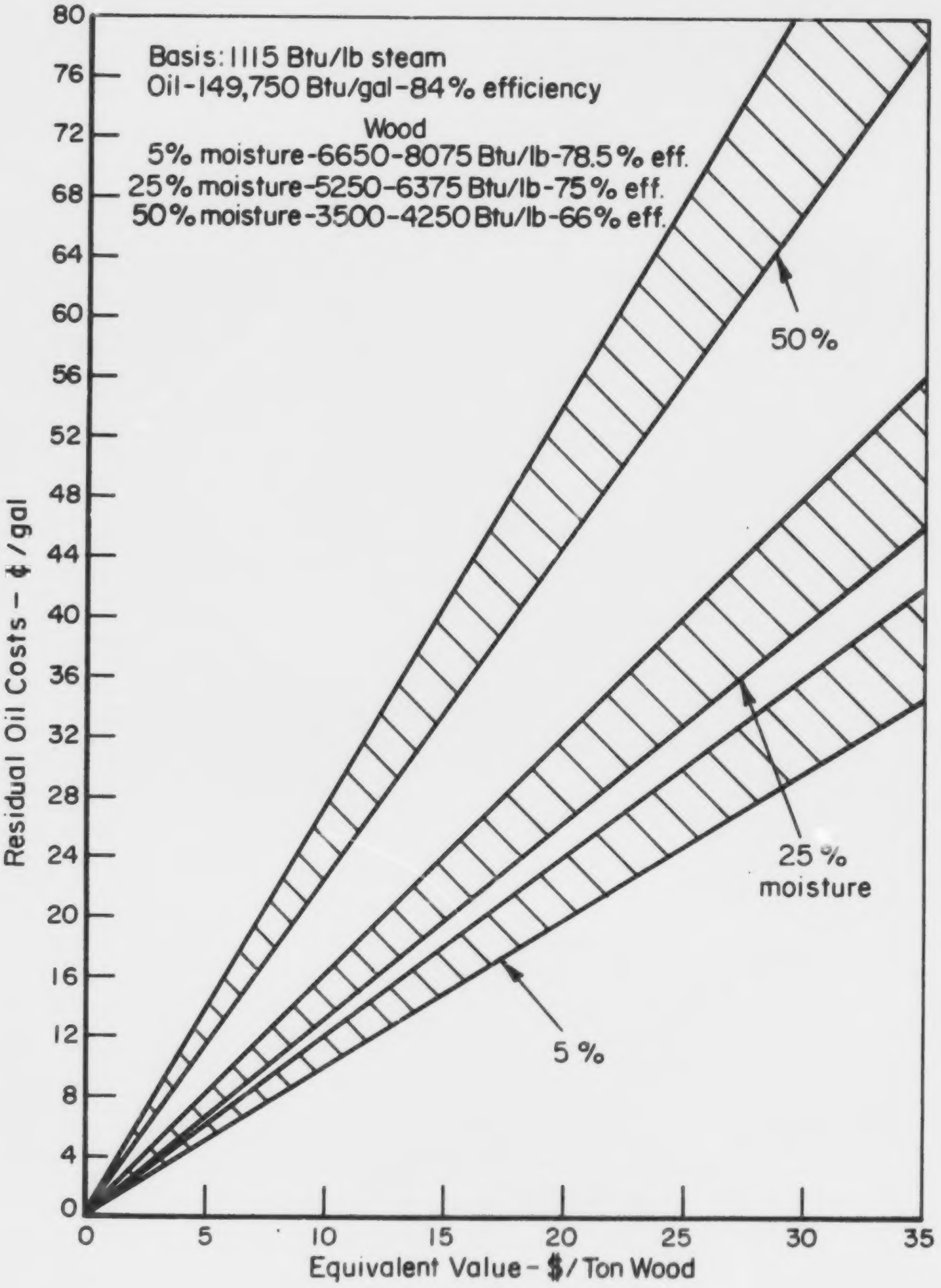

FIGURE 2. EQUIVALENT VALUE OF OIL AND WOOD AT 5, 25, AND 50 PERCENT MOISTURE

efficiency of the boiler is decreased. The efficiency penalty as a function of moisture content is discussed on page 40. The equivalent values of wood shown in Figures 1 and 2 are based on wood-fired boiler efficiencies of 78.5, 75, and 66 percent for moisture contents (wet basis) of 5, 25, and 50 percent. The comparable values for coal and oil used to develop Figures 1 and 2 are: 13,100 Btu/lb and 82 percent boiler efficiency for coal; and, 149,750 Btu/gal and 84 percent boiler efficiency for residual oil.

The sensitivity calculations result in a pair of lines, corresponding to 7,000 Btu/dry lb (the upper line of each pair), and 8,500 Btu/dry lb (the lower line of each pair) for each assumed moisture content; as shown in Figures 1 and 2. For example, if coal costs $55 per ton and and oil costs $0.32 per gallon (about $2.10/10^6 Btu for each), the equivalent value of wood as a boiler fuel as a function of heating value and moisture content would be as follows:

Moisture Content, Percent (wet basis)	Value of Wood Equivalent to Coal at $55/ton or Oil at $0.32/gallon	
	for 7,000 Btu/dry lb	for 8,500 Btu/dry lb
5	$26.75 per ton	$32.50 per ton
25	20.25 per ton	24.50 per ton
50	11.50 per ton	14.50 per ton

Viewed somewhat differently, Figures 1 and 2 show that if wood with a heating value of 8,500 Btu/dry lb and a moisture content of 25 percent (wet basis) could be purchased for $12.50 per ton it would be competitive with coal selling for $28.00 per ton or oil at 16.5 cents per gallon. On the other hand, if the wood has a heating value of only 7,000 Btu per dry lb, and a moisture content of 50 percent (wet basis), the $12.50 per ton price then would be competitive with coal at $47.50 per ton and oil at 28 cents per gallon.

This analysis shows that wood with a moisture content of 25 percent is about 75 percent more valuable than wood at 50 percent moisture, assuming the same heating value for the dry wood. It should be noted that this does not mean that one could buy a ton of green wood with 50 percent moisture, dry it to 25 percent moisture and, thereby, increase its value by 75 percent. An example will serve to illustrate. Compared to coal at $55/ton, wood with 8,500 Btu /dry lb and 50 percent moisture is worth $14.50 per ton. If a ton were dried to 25 percent moisture by removing 667 pounds of water, it would be worth $24.50 per ton, but since only 2/3 of a ton is left, the dried wood is worth only $16.33. The actual increase in value of nearly 13 percent results from the fact that the drier wood can now be burned with greater efficiency under the boiler.

Basic Assumptions

In the assessment of the use of wood as a fuel as compared with alternative fuels to be presented in subsequent sections, typical properties of wood were chosen as representative of wood fuel. These basic assumptions are as follows:

- Heating value, 8,500 Btu per pound of dry wood
- Moisture content, 45 percent (wet basis)
- Heating value, as received, 4,675 Btu/lb or 9.35×10^6 Btu/ton
- Steam boiler efficiency, 68.4 percent
- Overall power plant efficiency, 27.4 percent
- Power plant heat rate, 12,450 Btu/kwhr
- Plant capacity, 50 MW
- Load factor, 70 percent
- Calculated annual heat input, 3.8×10^{12} Btu/year
- Annual wood requirement, about 410,000 tons.

SUMMARY OF FINDINGS

Overview

The use of forest surplus and waste wood to fuel a new 50-MW power plant has been compared with the use of alternative fuels with respect to a number of different considerations. The general conclusions may be stated as follows:

- The use of forest surplus and waste wood is technically feasible
- Pollutant emissions are controllable
- Net energy balances are favorable
- The cost is competitive
- With proper forest management, there is potentially a net benefit to Vermont's forest ecosystem
- Wood is a renewable resource
- Therefore, a demonstration to advance the concept toward commercial application is recommended.

A summary of the comparisons between alternative fuels which lead to these conclusions is presented in Table 1. For each of several elements, quantitative or qualitative comparisons among the alternative fuels are shown. For some elements of comparison wood is better than other fuels, and for others it is worse. A very simple method used to obtain a comparison considering all elements is included in Table 1. For each element of comparison the alternative fuels were assigned rankings ranging from 1 (best alternative) to 5 (worst alternative). Where qualitative comparisons were found, or where subelements of comparison existed, the rank values were assigned arbitrarily and, to a degree, subjectively. Without attempting to assign weighting factors to the relative importance of the elements of comparison, the rank values for each fuel were summed to obtain an overall ranking. On this simplified basis the use of wood as a power-plant fuel has the lowest total and the dual wood-coal system has the second lowest total, therefore, both systems compare favorably with all of

TABLE 1. SUMMARY COMPARISONS OF ALTERNATIVE FUELS

	Alternative Fuels					
Element of Comparison	Wood	Low Sulfur Coal	Physically Cleaned Coal	HS Coal with Stack Gas Cleaning	Domestic Residual Oil	Dual, 75% Wood, 25% Cleaned Coal
1. General						
1.1 Renewable resource	Yes	No	No	No	No	Yes/No
Rank	1	3	3	3	5	2
2. Boiler Technology						
2.1 Equipment available	Yes	Yes	Yes	Yes	Yes	Yes
2.2 Boiler efficiency	.65-.8	.82	.82	.82	.84	.69-.81
Rank	5	3	3	3	1	4
3. Pollutant Emissions						
3.1 "Source-to-Power Total Air Emissions, 10^2 Tons/Year	38(a)	52	37-41	24-26	24	39(a)
3.2 Solid waste disposal problems	No	No	Yes	Yes	No	Yes
Rank	3	4	4	2	1	4
4. Energy Requirements						
4.1 Initial fuel required, 10^{11} Btu	38	32	36	35	32	36
4.2 "Source-to-Power" Energy Required, 10^{10} Btu	24	21	47	34	63	26
Rank	2	1	4	3	5	2
5. Cost						
5.1 1980 Est. cost of electricity, mils/kwhr	45	49	52	56	N.D.(b)	49
Rank	1	2	3	4	5	2
6. Ecological Impacts						
6.1 Net benefit to ecosystem	Yes	No	No	No	No	Yes/No
Rank	1	5	4	3	2	2
SUM OF RANK SCORES	13	18	21	18	19	16

(a) These values are too high if the NO_x emission factor has been overestimated. See Table 16, Page 94.

(b) N.D. - Not determined in the analysis but assumed higher than the other fules.

the alternative fuels. This result serves only to show that there are no overriding factors to prevent consideration of the use of wood to fuel incremental electric power generation capacity.

Specific Conclusions

Boiler Technology

1. The technology is available for burning wood under a boiler.
2. Vendors can supply wood-burning equipment. Between 1965 and March of 1975, 230 boilers with the capability to burn wood as the primary fuel or as an alternative fuel were sold in the United States.
3. Boilers for burning wood alone have not been sold in sizes larger than 500,000 pounds of steam per hour, roughly equivalent to 50 MWe.
4. Wood is often fired in combination with fossil fuels. This mode can be used if the projected availability of wood in a specific locale is insufficient to supply the input requirements for a large plant.
5. Drying the wood chips increases the boiler efficiency. It would not be prudent to use auxiliary fuel for this purpose, but waste heat from the plant could be used. The mechanics of this refinement were not covered in this study, however, a chip dryer, possibly of a fluidized-bed design, using heat extracted from the stack gases appears feasible. The benefits in reduced green wood handling and reduced fuel input warrant a thorough analysis of this concept.

Pollutant Emissions and Control Technology

1. The use of waste wood to fuel boilers for the generation of electricity is an environmentally acceptable method of power generation.

2. Total emissions for wood-fueled systems are significantly less than acceptable alternative fuels such as physically cleaned coal or low-sulfur Western coals.
3. Control technology for the collection of up to 99.9 percent of the particulates is currently available. The most promising control method identified is a multitubular cyclone separator connected in series with a low-energy wet-impingement scrubber. This system has proven economical, dependable, and effective in actual waste wood boiler application.
4. Emission of hazardous organic chemicals from the incomplete combustion of wood should not present any significant problems to the local air quality.
5. Environmentally acceptable disposal of boiler residues can be accomplished by placing the relatively inert boiler ash and fly ash in landfills or in lagoons.

Energy Balances

1. A larger fuel input is required because of reduced boiler efficiency associated with firing wood. Wood with 45 percent moisture (wet basis) requires 3.8×10^{12} Btu/year compared with 3.22×10^{12} Btu/year for coal. Wood dried to 15 percent moisture (wet basis) requires an input of 3.4×10^{12} Btu/year. This is less than the mined coal requirement for all coal paths except low sulfur western coal.
2. Energy consumptions for recovery or procurement, for processing, and for transportation of fuel are lower for green wood than all other alternatives except low sulfur western coal and imported oil. These quantities are even more favorable for dried wood.

Cost Comparison

1. The cost of green wood chips delivered to the power plant is estimated to be:

Item	Estimated Cost, $/ton 1975	 1980 (7% inflation)
Stumpage or procurement	0.36	0.50
Harvesting	7.60	10.65
Chipping	1.43	2.01
Transportation	1.25	1.75
Total	10.64	14.91

2. The cost of electricity produced by alternative fuels is **estimated by this preliminary analysis to be:**

Fuel	Cost of electricity, mils/kwhr in 1980
Green wood chips	45.2
Green wood and physically cleaned coal	49.0
Low sulfur coal	49.2
Physically cleaned coal	51.9
HS coal with stack gas scrubbing	55.9

3. **According to this preliminary analysis, green wood chips are competitive in cost with all alternative fuels.**
4. The estimated cost of electricity for a wood-fueled plant is quite sensitive to wood fuel costs, and moderately sensitive to plant size; but relatively insensitive to transportation costs and pollution control costs. Harvesting accounts for 81 percent of wood fuel costs, whereas procurement accounts for only 4 percent and chipping for 15 percent.

Environmental-Ecological Impacts

1. With sound forest management practice, the use of forest surplus as fuel can, on balance, be of benefit to the overall forest ecosystem.
2. The effect of nutrient removal by harvest is not completely known at this time. Available data are site specific and are difficult to project to other sites.

3. Nutrient inputs to forests are variable and are not yet fully quantified. Natural replacement of nutrients may be entirely sufficient for projected management alternatives. The natural process can be supplemented by fertilization if required.
4. Proper forest management practices have been defined for mitigating potential impacts on water quality and soil errosion.
5. Properly planned cutting of timber stands tends to improve wildlife habitat.
6. Good management can minimize visual impacts of timber cutting.

Applicability of the Concept to Other Regions

1. Conservative estimates of surplus and waste forest biomass show an availability equal to 23 to 103 percent of the utility fuel requirements in the New England, South Atlantic, East South Central, Mountain, and Pacific regions.
2. In the South Atlantic, Mountain, and Pacific regions, the estimated surplus wood availability represents 77, 118, and 103 percent, respectively, of the combined oil and gas consumption by utilities.
3. Wood fuel is cost competitive with other fuels in most of these regions, therefore, the concept appears to be applicable in at least five regions of the country for incremental electric power capacity additions.
4. All-wood-fired boilers currently are not sold in sizes larger than 500,000 pounds per hour of steam (approximately equal to 50 MWe). Larger plants could be built using multiple boilers. The normal economies of scale would not apply.
5. Procurement, transportation, and storage problems may limit the maximum size of a single wood-fired plant to 200-250 MWe.

Use of Milton Plant for Demonstration

(1) The boilers, turbine-generator, and the plant auxiliaries have been maintained well and seem to be adequate for a few years of service under adequate care and operations.

(2) There are no apparent reasons why the plant cannot be adapted to burn wood chips. However, the physical arrangement of the boilers is not preferred for burning such fuel. The deficiencies and countermeasures which may overcome them are discussed in the report.

(3) Plant modifications are discussed including the systems required for chip unloading and storage, chip retrieval from storage and conveying into the existing boiler house, chip feeding to the boilers, grate system, combustion air supply, flyash collection, and ash removal.

(4) The equipment to modify the plant is currently available as standard production items. Delivery may be as long as one year for the stokers.

(5) The cost of the modification of the plant including engineering is estimated at $680,000.

(6) With regard to the possibility that the planned research program might include the development of design and performance factors relative to burning wood chips to generate steam, the value of data which can be obtained is questionable because, as mentioned above, the boiler configuration is not typical of modern design for burning such fuels. If the research is extended into the fields of combustion and pollution control, attention to the boiler deficiencies will be imperative and qualified engineers should play a key role in the entire project.

(7) Uncontrolled particulate emissions from the Milton Plant are projected to yield particulate concentrations in excess of allowable ambient air quality levels.

(8) Increasing the stack height by 20 feet would not be expected to alter the foregoing conclusion.

(9) Nominal 80 percent particulate control would reduce the projected ambient particulate concentrations to acceptable levels. However, at these control levels particulate and odor emissions may prove to be pollution problems to the town of Milton.

SUMMARY OF BOILER TECHNOLOGY

A boiler by definition is a mechanical device for converting water to steam. This steam can then be used for a variety of purposes but the first and primary purpose in America was for powering steam engines. The first American water tube boiler was patented by John Stevens in 1803, for powering a riverboat on the Hudson River(1)*. This first type of boiler, shown in Figure 3, consisted of a series of tubes extending radially outward from a central reservoir which, when heated, produced saturated steam. This design was limited and enjoyed little success. In 1805, however, John Cox Stevens, son of John Stevens, patented a two-drum boiler, shown in Figure 4, consisting of a lower chamber connected to an upper chamber by a series of tubes. Water in the lower chamber is converted to steam when heat is applied to the connecting tubes and the steam is collected in the upper chamber. This two-chamber or two-drum concept of boiler design is common in many modern boilers manufactured today.

In 1881, the first central power station for generating electric power from steam went into service at the Brush Electric Light Company plant in Philadelphia, Pennsylvania (1). This plant consisted of four 73-horsepower boilers which is roughly equivalent to 10,000 pounds of steam per hour total** or 1 megawatt at an overall cycle efficiency of 33 percent. Over the years boiler size and complexity as well as steam temperatures and pressures have increased dramatically. This evolution has taken place most rapidly in the last 50 years with power plant unit sizes going from 60 megawatts in 1925, to units over 1000 megawatts in 1975.

One of the big factors allowing this drastic increase in boiler size was the introduction of pulverized coal firing which began to replace other forms of solid fuel firing in the 1930's.

Coal, when pulverized to talcom powder consistency, can be fired into a boiler similar to a gas or liquid fuel eliminating the need for grates and increasing the heat release possible in a given furnace volume.

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* References for this section are given on page 57

** 1 boiler horsepower is equivalent to 34.5 pounds of steam per hour or 10 ft^2 of heating surface (1).

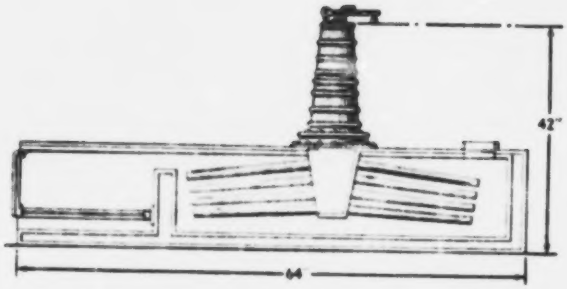


FIGURE 3. EARLY DESIGN OF WATER-TUBE BOILER
Source: Reference 1, Fig. 2, p 1-3.

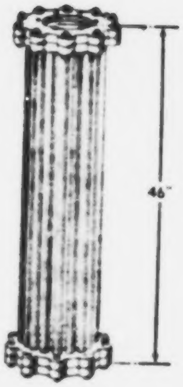


FIGURE 4. IMPROVED DESIGN OF WATER-TUBE BOILER
Source: Reference 1, Fig. 3, p 1-4.

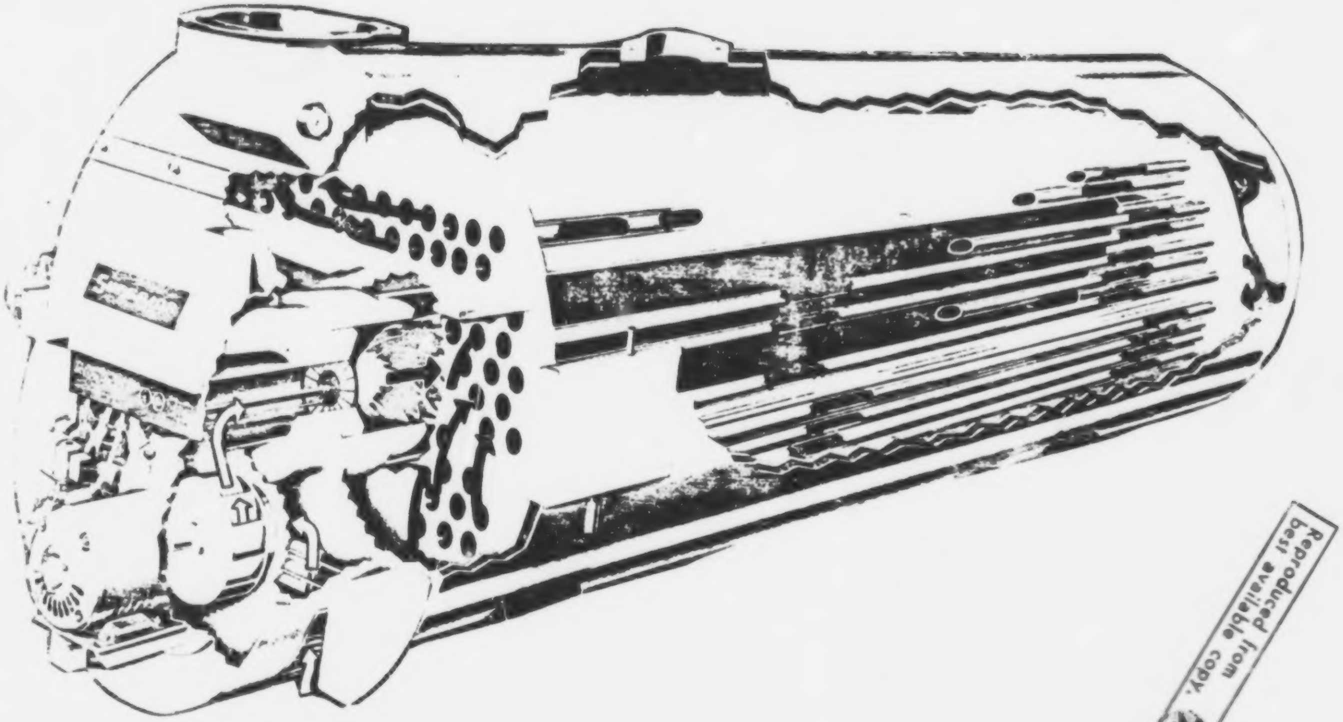
Basic Boiler Types

Boilers can generally be classified by design as either firetube or watertube. In a firetube boiler (shown in Figure 5), as the name implies, the combustion takes place on the inside of the heat transfer tubes and this heat is absorbed by the water which is contained by the boiler shell on the outside of the tubes. This type of boiler is generally limited to small sizes (seldom exceeding 20,000 pounds steam per hour) and to low pressure (less than 100 psig). Firetube boilers could possibly be fired with solid fuels but in recent years almost all firetube boilers sold were designed to fire natural gas or oil and would be unsuitable for solid fuel firing.

In watertube boilers, water and steam is contained in the heat-transfer tubes and the combustion takes place on the outside contained by the furnace walls. In older watertube boiler designs, the furnace walls were comprised of refractory brick which acted as an insulator around the combustion zone. The trend in watertube boiler design, however, has been towards the use of water tubes for walls using the heat absorbed by the walls to raise steam. In the case of hard-to-combust fuels with low volatility, low heat value, or high moisture such as anthracite, municipal refuse, or wood, refractory walls are still used to maintain sufficiently high furnace temperatures to insure adequate combustion. Such designs, however, limit the amount of heat that can be absorbed by the furnace, thus decreasing boiler efficiency.

Watertube boilers are manufactured in a variety of configurations depending on the fuels they are designed to fire. According to a recent survey of watertube boilers sold in an 8-year period from 1965 to 1973(2), 57 percent of all boilers sold were designed for natural gas as a primary fuel, 28 percent were designed for oil, 6.4 percent for bituminous coal, and 1.6 percent for wood bark.

It is important, however, to distinguish between boilers above 500,000 pounds steam per hour or 50 megawatts (primarily utilities) and those below 500,000 pounds steam per hour (primarily industrial boilers). For boilers over 500,000 pounds steam per hour sold between



Reproduced from best available copy.

FIGURE 5. FIRETUBE BOILER (COURTESY OF SUPERIOR COMBUSTION CORPORATION)

1965 and 1973, 47 percent were coal fired, 25 percent oil fired, 21 percent gas fired, and 1.3 percent designed primarily for wood firing. For boilers under 500,000 pounds steam per hour, only 3.9 percent were designed primarily for coal, 27 percent for oil, 57 percent for gas, and 1.4 percent for wood. This comparison shows that in the larger sizes dominated by utilities (over 50 megawatts electric generating capacity) coal is the dominant fuel. In the smaller sizes, however, coal and other solid fuels account for a relatively small fraction of boiler sales.

Effect of Fuel Characteristics on Boiler Design

The particular fuel a boiler is designed to burn has a considerable effect on its design. Boilers designed for clean fuels such as natural gas or oil generally have no provision for installation of grates for firing lump-size solid fuels, nor do they have ash handling facilities or soot blowers for cleaning ash deposits off heat transfer surfaces. Also, to maintain compact, low cost design, tube spacing is usually kept to a minimum allowing for no ash buildup on tube surfaces. As a result it is not considered attractive to fire solid fuels such as coal or wood in boilers specifically designed for clean fuels such as gas or oil. According to the population survey made in 1973(2) only 0.1 percent of boilers designed for natural gas list either coal or wood bark as an alternative fuel. Of boilers designed for oil, only 0.4 percent can burn coal.

Boilers designed for dirty fuels such as coal and wood, however, frequently are also capable of burning clean fuels as alternatives. For instance, 7.6 percent of the boilers designed for coal sold between 1965 and 1973 list oil as an alternative fuel and 9.5 percent list natural gas. Of the wood-burning boilers, 21 percent list oil as an alternative and 23 percent list natural gas. Boilers designed for wood, coal, or other ash-containing fuels, have certain design features in common.

- Ash handling facilities for removing bottom ash to disposal area.

- Soot blowing equipment for periodically cleaning ash deposits off heat transfer surfaces.

- Wider tube spacings and more generous furnace volumes to allow for ash deposits on heat-transfer surfaces.
- Allowances for installation of pollution control equipment, particularly for fly ash control.
- Fuel storage, handling, and preparation equipment for receiving and storing an adequate fuel supply, reducing it to a desired size and possibly reducing its moisture content,and equipment for conveying the fuel to the boiler for firing.

Coal as a Fuel

Coal has its origin in wood and other cellulosic materials which, after millions of years of compression, under the earth's surface, gradually underwent evolution to various grades of coal. Compositions for the common ranks of coal as they progress in time of evolution from the starting material, wood are shown in Table 2. These various materials can be generally classed as to their carbon content as a fuction of age. As the age or evolutionary state increases, the fixed carbon (FC) content increases from around 20 percent for wood to over 80 percent for meta-anthracite, the oldest form of coal. The heat value also tends to increase up through the bituminous series and then declines for the anthracites as the hydrogen content decreases. An important difference between the starting material, wood and the various forms of coal is the ash and sulfur which originates from the soil conditions present in the coal deposit that become an integral part of the coal. These constituents are present in wood in only small amounts by comparison.

Coal has long been a standard fuel for utility boilers and will continue to be for some time to come due to its relative low cost and high availability compared to other fuels. Boilers designed for coal, however, entail inherently higher cost than those designed for either gas or oil. This higher cost can be justified in utility applications due to long plant life and high plant utilization factors. In industrial size boilers, under 500,000 lbs steam per hour, coal fired boiler sales have decreased considerably in the last 10 years in favor of gas and oil-fired units. In 1965, 11 percent of all boilers sold under 500,000 lbs steam per hour were coal fired whereas in 1972 only 1.1 percent were coal fired(2).

The type of firing method and equipment design employed for coal burning depends both on coal properties and on boiler size. There is a strong dependence of firing method on size particularly between pulverized or suspension firing and firing on a grate with various types of stokers.

Table 2. Progressive Stages of Transformation of Vegetal Matter into Coal(3)

Fuel Classification by Rank	Locality	Moisture (as-received)	Analysis on dry basis								Heating value Btu (dry basis)
			Proximate			Ultimate					
			VM	FC	Ash	S	H_2	C	N_2	O_2	
Wood		46.9	78.1	20.4	1.5		6.0	51.4	0.1	41.0	8835
Peat	Minnesota	64.3	67.3	22.7	10.0	0.4	5.3	52.2	1.8	30.3	9057
Lignite	North Dakota	36.0	49.8	38.1	12.1	1.8	4.0	64.7	1.9	15.5	11036
Lignite	Texas	33.7	44.1	44.9	11.0	0.8	4.6	64.1	1.2	18.3	11084
Subbituminous C	Wyoming	22.3	40.4	44.7	14.9	3.4	4.1	61.7	1.3	14.6	10598
Subbituminous B	Wyoming	15.3	39.7	53.6	6.7	2.7	5.2	67.3	1.9	15.2	12096
Subbituminous A	Wyoming	12.8	39.0	55.2	5.8	0.4	5.2	73.1	0.9	14.6	12902
Bituminous High Volatile C	Colorado	12.0	38.9	53.9	7.2	0.6	5.0	73.1	1.5	12.6	13063
Bituminous High Volatile B	Illinois	8.5	35.4	56.2	8.4	1.8	4.8	74.5	1.5	8.9	13388
Bituminous High Volatile A	Pennsylvania	1.4	34.3	59.2	6.5	1.3	5.2	79.5	1.4	6.1	14396
Bituminous Medium Volatile	West Virginia	3.4	22.2	74.9	2.9	0.6	4.9	86.4	1.6	3.6	15178
Bituminous Low Volatile	West Virginia	3.6	16.0	79.1	4.9	0.8	4.8	85.4	1.5	2.6	15000
Semianthracite	Arkansas	5.2	11.0	74.2	14.8	2.2	3.4	76.4	0.5	2.7	13142
Anthracite	Pennsylvania	5.4	7.4	75.9	16.7	0.8	2.6	76.8	0.8	2.3	12737
Meta-anthracite	Rhode Island	4.5	3.2	82.4	14.4	0.9	0.5	82.4	0.1	1.7	11624

In the size range above 500,000 lbs steam per hour, 86 percent of the boilers sold from 1965 to 1973 designed for coal were equipped with pulverized coal fired systems. No stoker fired boilers were recorded in this size range; however, in the size range under 500,000 lbs steam per hour 63 percent were stoker fired (41 percent spreader stoker, 9 percent underfeed stoker, and 13 percent overfeed stoker). In contrast only 10 percent were pulverized fired in this size range.

Pulverized coal furnaces are fired in a similar fashion to gas and oil fired furnaces. An example of a central station pulverized coal fired boiler is shown in Figure 6. The coal first is reduced to a very fine size usually gaged as the number of particles that will pass a 200 mesh screen having 200 openings per linear inch, or each opening 74 microns in size. Normally, around 60 to 75 percent of the coal particles would be required to pass a 200 mesh screen to be considered acceptable for watertube boilers.(3) This fine size allows rapid combustion and high heat release rates.

The pulverizer itself normally consists of a set of steel balls or rollers held between two races. As the races are rotated against each other the coal is crushed between the ball surface and race surface. A side view of a double ball and race pulverizer is shown in Figure 7. The crushed coal is then picked up in an upward flowing air stream which selects for smaller coal particles as the larger particles are not entrained and fall back into the pulverizer.

Pulverizer capacity is primarily a function of fuel moisture content, size, and grindability. Hot air is usually supplied to the mill to promote drying of the coal while pulverizing. If this air supply is not sufficient then mill capacity may be reduced due to agglomeration of the moist coal particles making it difficult to remove them from the mill. Commercial pulverizers can commonly handle up to 20 percent total moisture (15 percent surface moisture)(1) without seriously affecting capacity.

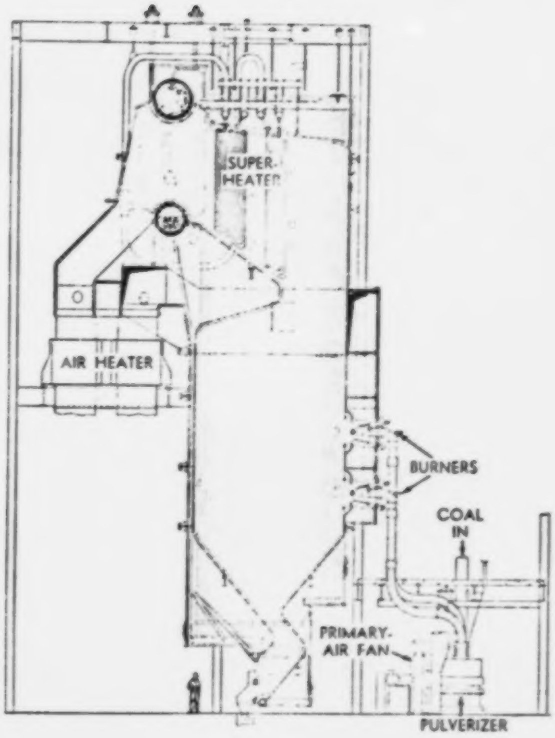

SUPER-
HEATER
AIR HEATER
BURNERS
COAL
IN
PRIMARY-
AIR FAN
PULVERIZER

FIGURE 6. PULVERIZED COAL-FIRED BOILER

Source: Reference 1, Fig. 6, page 17-6.

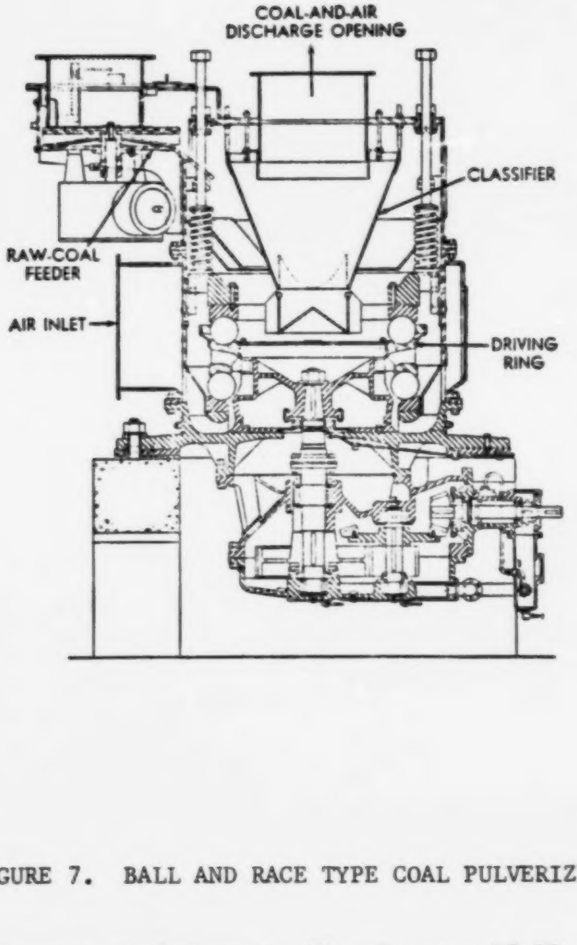

COAL-AND-AIR DISCHARGE OPENING
CLASSIFIER
RAW-COAL FEEDER
AIR INLET
DRIVING RING

FIGURE 7. BALL AND RACE TYPE COAL PULVERIZER

Source: Reference 1, Fig. 9, page 17-10.

Coal size is also an important factor in determining pulverizer capacity. Ideally the coal would be double screened to restrict the size to about 3/4 x 1/4 inch.(1) Usually coal is fed to pulverizers as run of mine or screenings with lumps though large inconsistencies in size will result in reduced capacity.

The grindablility of a coal is a measure of the relative ease with which a coal can be crushed. The grindability is measured in a Hardgrove grindability machine which is a standard ball and race type pulverizer that is operated under a specific set of conditions. The power required to pulverize a given amount of coal is a measure of its grindability and is usually expressed as the Hardgrove Grindability Index. The effect on mill capacity is about directly proportional to the index. Western lignitic coals may have low grindabilities, around 50, whereas harder Eastern coals may range to 100 or more.

Once the coal is pulverized it is pneumatically conveyed to a series of burners and fired into the boiler. Various firing configurations can be used but the most common are to fire horizontally from either one wall or opposing walls of the furnace or to fire tangentially into the center of the furnace from the four corners. Approximately 10 to 15 percent excess air is customarily supplied with the fuel to insure complete combustion.

After combustion about 80 percent of the ash in the fuel is carried away with the flue gas(1) and must be removed in downstream particulate removal devices. The remainder of the ash falls to the bottom of the furnace where it is normally quenched in water and sluiced to an ash settling pond.

Most all large and small coal fired boilers today operate in a so-called dry bottom mode, where furnace temperatures are kept low enough to prevent the ash from becoming molten, usually below the ash fusion temperature of the coal. Some furnaces, however, are intentionally operated at higher temperatures above the melting point of the ash in a so called wet bottom or slagging mode. An example of this type of furnace is the cyclone design shown in Figure 8. The cyclone burner itself is

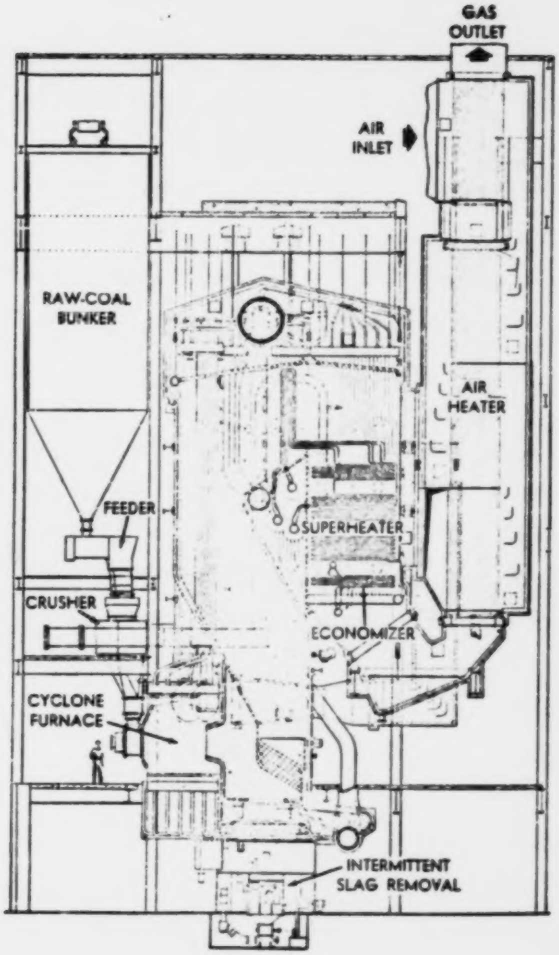

GAS OUTLET
AIR INLET
RAW-COAL BUNKER
AIR HEATER
FEEDER
SUPERHEATER
CRUSHER
ECONOMIZER
CYCLONE FURNACE
INTERMITTENT SLAG REMOVAL

FIGURE 8. CYCLONE FURNACE

Source: Reference 1, Fig. 14, page 28-8.

is shown in Figure 9. Coal, along with conveying air, is introduced tangentially into the cyclone burner which consists of a water cooled horizontal cylinder. The ash in the fuel melts and is thrown outward to the burner walls where it is removed by a slag tap at the base of the burner. The hot gases from the burner then go through a conventional heat recovery boiler as is shown in Figure 8. Heat release rates of up to 900,000 Btu/ft^3/hr and gas temperatures exceeding 3000 F are developed in the burner section. Slagging furnaces are not recommended for fuels with ash fluid temperatures over 2600 F or ash viscosity greater than 250 poises at 2600 F.$^{(1)}$

The cyclone boiler is the type of slagging boiler to be most significantly employed on a utility scale though many older slagging boilers are still operating that are not cyclones. Recently, however, few of these boilers have been installed due to their interent propensity for emitting high levels of NO_x to the atmosphere. The high gas temperatures achieved in the burner causes fixation of airborne nitrogen to NO_x.

Stoker fired coal boilers are most commonly found in the size range from about 25,000 to 250,000 lbs steam per hour. Stokers offer lower capital cost than pulverized fired systems because they don't require pulverizers and related equipment.

The stoker itself is simply a means for conveying lump size coal to the combustion zone and removing the ash to an ash pit on a more or less continuous basis. Modern stokers can be classed into three types, overfeed, spreader, and underfeed stokers.

Overfeed stokers are typified by the traveling grate arrangement shown in Figure 10. The stoker consists of a continuous rotating belt. Coal is deposited on one end of the belt and progresses through the combustion zone where combustion air is supplied from plenum chambers under the grate. The ash remaining after combustion is discharged to an ash pit off the end of the grate.

Another type of overfeed stoker is one involving a vibrating grate shown in Figure 11. This stoker consists of an inclined grate with a series of verticle plates that are free to move back and forth

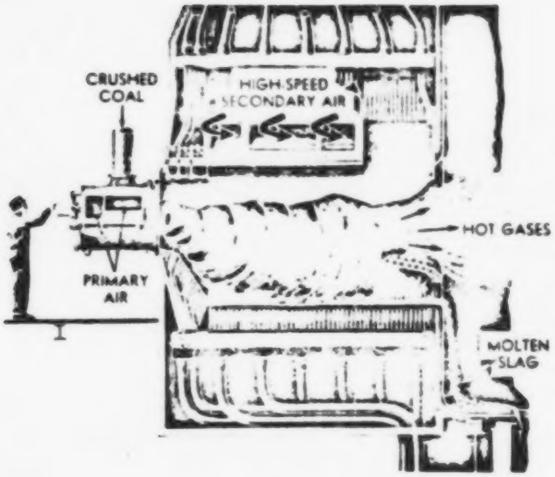

CRUSHED COAL
HIGH-SPEED SECONDARY AIR
HOT GASES
PRIMARY AIR
MOLTEN SLAG

FIGURE 9. CYCLONE BURNER

Source: Reference 1, Fig. 1, page 28-2.

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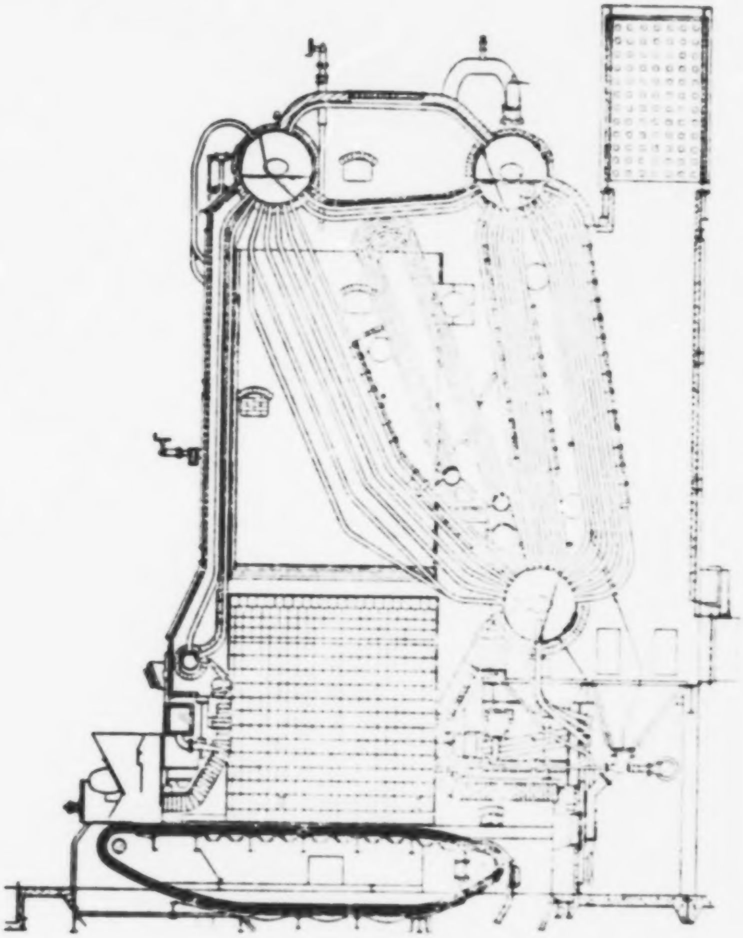

FIGURE 10. TRAVELING GRATE STOKER

Source: Reference 4.

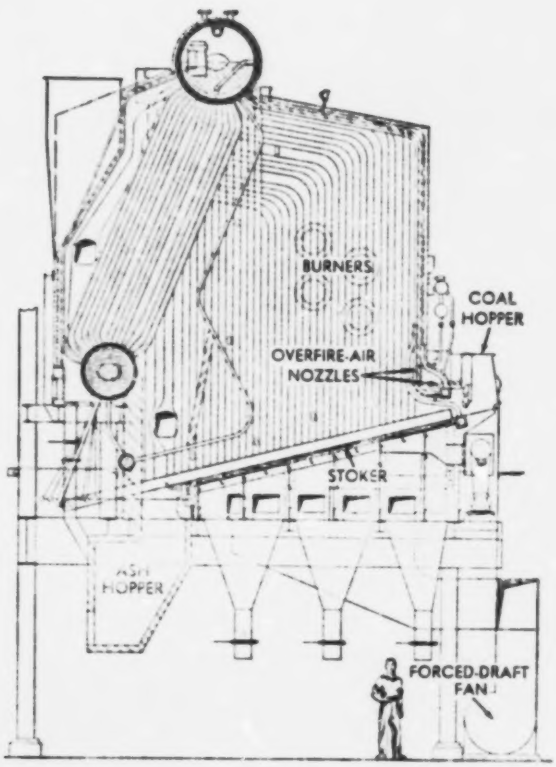
BURNERS
COAL HOPPER
OVERFIRE-AIR NOZZLES
STOKER
ASH HOPPER
FORCED-DRAFT FAN

FIGURE 11. VIBRATING GRATE STOKER

Source: Reference 1, Fig. 7, page 16-9.

in a rectilinear motion. This motion causes the coal to descend down the grate through the combustion zone to the end of the grate where the ash is discharged to an ash pit.

A spreader stoker shown in Figure 12 is a special case of an overfeed traveling grate, although stationary or intermittent dumping grates may also be used. Instead of the coal being deposited on one end of the grate, it is flipped or projected from one wall of the furnace through the combustion zone in suspension. Much of the fuel burns in suspension and the remainder falls to the grate where burning is completed in a fast burning thin fuel bed. The advantages of this type of operation are better response to load changes and greater ability to handle a wide variety of coals.

The fuel bed on a spreader stoker is relatively thin and ususally ranges from 2 to 4 inches. Heat release rates are high with stationary or dumping rates achieving 450,000 Btu/ft^2/hr and traveling rates up to 750,000 Btu/ft^2/hr. The spreader stoker is limited in its ability to handle low loads, however, as the fire tends to smoke at loads below 125,000 Btu/hr/ft^2. (3)

Underfeed stokers are somewhat different in principle than overfeed or spreader types. An example of an underfeed unit is shown in Figure 13. Coal is fed to the combustion zone by a screw type feeder from under the bed, which is contained in a retort, and combusion takes place on top of the bed . The ash is then removed off the sides.

Generally stokers require carefully sized coal for most efficient operation. The most important considerations are to limit coal sizes over 2 inches and those less than 1/4 inch (referred to as slack). The exception to this rule is the spreader stoker which operates best with coal less than 3/4 inch including fines or slack (3). Also the traveling grate stoker is limited to burning coals with low caking tendencies such as anthracites, lignites and some free burning butiminous coals.

Also overfire air amounting to 5 to 15 percent of combustion air or steam is generally injected just above the combustion zone in stoker applications to promote turbulence and mixing. This practice stimulates combustion and reduces smoke emissions.

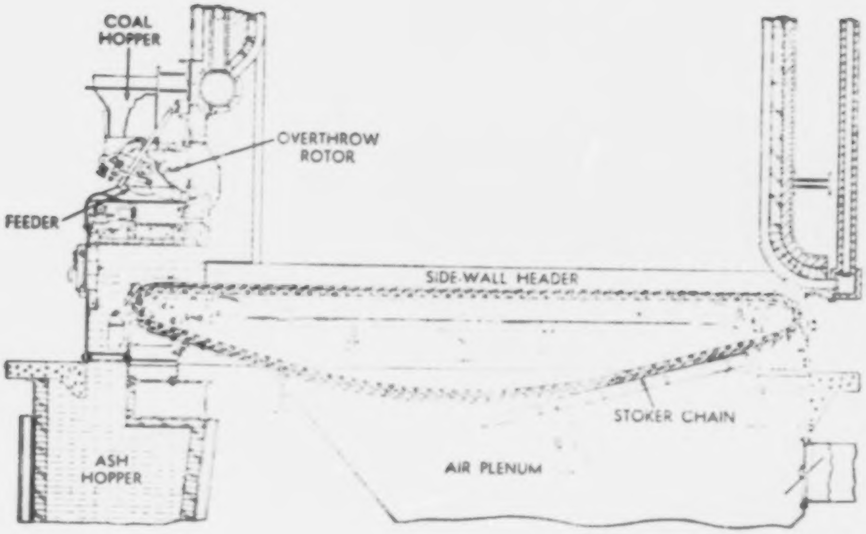
COAL HOPPER
OVERTHROW ROTOR
FEEDER
SIDE-WALL HEADER
STOKER CHAIN
ASH HOPPER
AIR PLENUM

FIGURE 12. SPREADER STOKER

Source: Reference 1, Fig. 11, page 16-12.

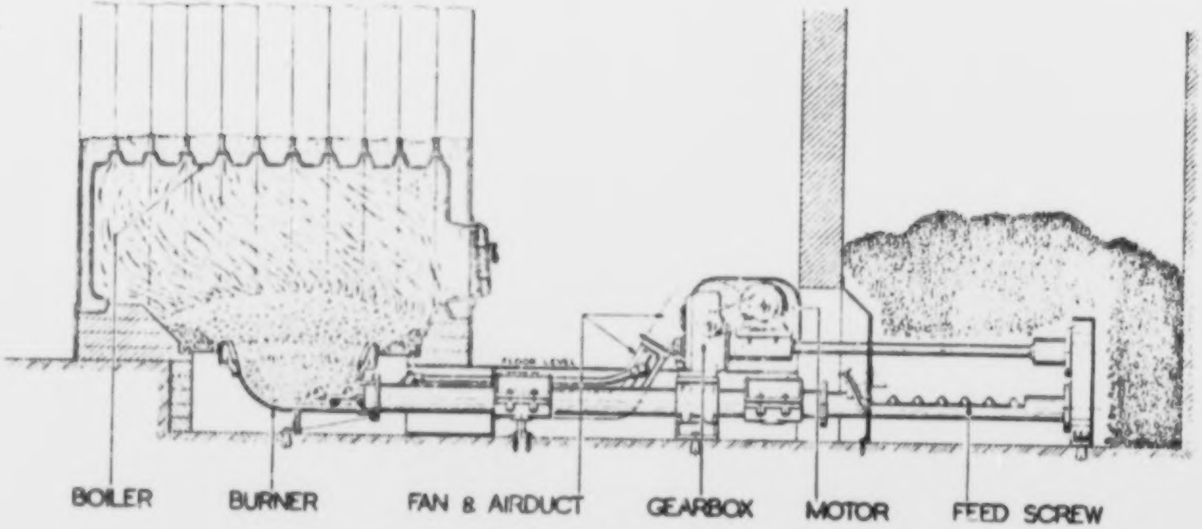
FLOOR LEVEL
BOILER
BURNER
FAN & AIRDUCT
GEARBOX
MOTOR
FEED SCREW

FIGURE 13. UNDERFEED STOKER

Source: Reference 4.

Wood As A Fuel

Typical composition of various types of wood and the resulting ash composition of the wood when burned are shown in Table 3. Wood consists primarily of 90 to 95 percent cellulosic material with 5 to 10 percent volatiles, resins, fatty acids and other non-cellulosic materials(8). Wood itself has a heating value of about 8,300 Btu/per dry lb, whereas resins and other materials have heating values of about 16,900 Btu per lb. Woods containing high amounts of resin material, therefore, have a higher heating value than woods containing lesser amounts. As is shown in Table 3, resinous woods, such as pine and fir, have heating values of close to 9,000 Btu per dry lb, whereas harder woods, such as oak, having heating values closer to 8,300 Btu per dry lb.

In wood processing about 50 percent of the weight of the raw wood ends up as residue or waste. This residue is broken down roughly into 18 percent slabs edgings and trimmings, 10 percent bark, and 20 percent sawdust and shavings(3). Much of the residue, particularly slabs, edgings and trimmings, is processed through a machine called the hogger, which reduces the size of the wood making it more manageable and easier to burn. This so called hog fuel may contain on the average about 50 percent moisture, but the moisture content can vary considerably, depending on the particular type of wood processing involved. Other than the moisture content wood shows a remarkably uniform composition. It usually contains less than 1 percent ash and little or no sulfur, making it an ideal fuel.

Today, 43 percent of the world's wood is burned as a fuel which is its largest single use.(9) The high moisture content in the wood has the biggest effect on its value as a fuel. As the moisture content increases the heating value of the wood correspondingly decreases. In addition to reducing the heating value of wood, moisture also diminishes furnace efficiency, as heat required to evaporate the water is lost in the stack gases. This heat requirement is such that as the moisture content approaches 60 percent, it becomes difficult to maintain steady combustion. As the moisture content goes to 70 to 80 percent, the wood no longer has sufficient heat content to support its own combustion and becomes useless waste.(3) Wood can be dried by a variety of means. For example large presses can be used to squeeze excess moisture out of the wood and can potentially reduce moisture from around 70 per cent down to 55 to 66

TABLE 3. ANALYSES OF WOOD AND WOOD ASH*

Column No.*		1	2	3	4	5	6
Wood Analyses (Dry Basis), % by wt							
Proximate							
Volatile matter		72.9	76.0	74.7	74.3	69.6	72.6
Fixed carbon		24.2	18.7	23.3	24.0	26.6	27.0
Ash		2.9	5.3	2.0	1.7	3.8	0.4
Ultimate							
H_2	Hydrogen	5.6	5.4	5.7	5.8	5.7	5.1
C	Carbon	53.4	49.7	53.9	52.2	51.8	51.9
S	Sulfur	0.1	0.1	trace	trace	0.1	trace
$N_2 + O_2$	Nitrogen + Oxygen	38.0	39.5	38.4	40.3	38.6	42.6
A	Ash	2.9	5.3	2.0	1.7	3.8	0.4
Heating value, Btu/lb		9030	8370	9120	8810	8740	8350
Ash Analyses, % by wt							
Silica	as SiO_2	–	–	–	1.7	32.0	14.3
Iron	as Fe_2O_3	–	–	–	3.2	6.4	3.5
Titanium	as TiO_2	–	–	–	0.0	0.8	0.3
Aluminum	as Al_2O_3	–	–	–	3.2	11.0	4.0
Manganese	as Mn_3O_4	–	–	–	3.9	1.5	0.1
Calcium	as CaO	–	–	–	60.8	25.3	6.0
Magnesium	as MgO	–	–	–	3.0	4.1	6.6
Alkalies	as Na_2O	–	–	–	10.4	10.4	25.0
Sulfate	as SO_3	–	–	–	3.0	2.1	7.4
Chloride	as Cl	–	–	–	0.4	trace	18.4
Carbonate	as CO_2	–	–	–	11.5	7.0	14.0
Undetermined		–	–	–	–	–	–
Ash-fusion temperatures		†	‡	–	–	–	–

*Col No.	Kind of Wood
1	Southern pine bark
2	Oak bark
3	Oregon wood, hogged
4	White-fir bark, salt-water stored
5	Spruce bark, salt-water stored
6	Redwood bark, salt-water stored

Ash-Fusion Temperatures, F

	Reducing		Oxidizing	
	†	‡	†	‡
Initial Deform.	2180	2690	2180	2680
Softening	2220	2720	2220	2730
Fluid	2340	2740	2470	2750

---

* Reference 1, page 3-A4.

percent, making the wood acceptable to many types of fuel burning equipment(10). Air drying can reduce moisture content of freshly cut wood from 50 percent down to 25 percent in about a year(3). Hot air, using heat from boiler flue gas, could be used to partially dry the woods.

Heat losses in the burning of wood consists mainly of those due to moisture in the stack gas and the heat left in the stack gas after combustion. Other losses consist of radiation and miscellaneous heat losses from the boiler and carbon loss in the ash.

Loss in boiler efficiency as a function of moisture content of the wood is shown in Figure 14(9). This loss is a small function of the temperature of the stack gases; however, the large bulk of the heat loss is attributable to the latent heat of vaporization of the water vapor in the stack gas. As can be seen in Figure 14, this can amount to 13 percent in efficiency loss for 50 percent moisture in the wood or up to 26 percent loss for a moisture content of 67 percent. The heat loss in the dry stack gases is a significant function of the amount and temperature of the stack gas. The amount of stack gas is dependent upon the amount of excess air used for combusting the wood and also the moisture content of the wood. A moisture content of 50 percent can, in fact, increase the volume of flue gas up to 50 percent(11). The loss in boiler efficiency due to heat in the stack gases is around 9 percent for 500 degree stack gas and 40 percent excess air, and this would increase to 14 percent for 100 percent excess air.(9) With heat recovery equipment, such as combustion air preheaters and economizers or feed water heaters, the stack gas temperature can be reduced from 500 F down to 300 F. This would reduce the efficiency loss to 5 percent for 40 percent excess air and 6 percent for 100 percent excess air. A summary of these heat losses is given in Table 4. Data are given for moisture content values of 5, 25, and 50 percent (wet basis). The resulting boiler efficiencies are 78.5, 75, and 66 percent, respectively.

Wood is commonly burned in a variety of types of equipment. Prior to about 1940 the most common method was to burn the wood in a dutch oven which is shown in Figure 15. Wood is usually fed in through the top of the oven and is left to pile up usually on some form of water-cooled grate. Combustion air is fed through the sides of the cell and grate causing the wood to be gasified and combusted. The hot gases are then

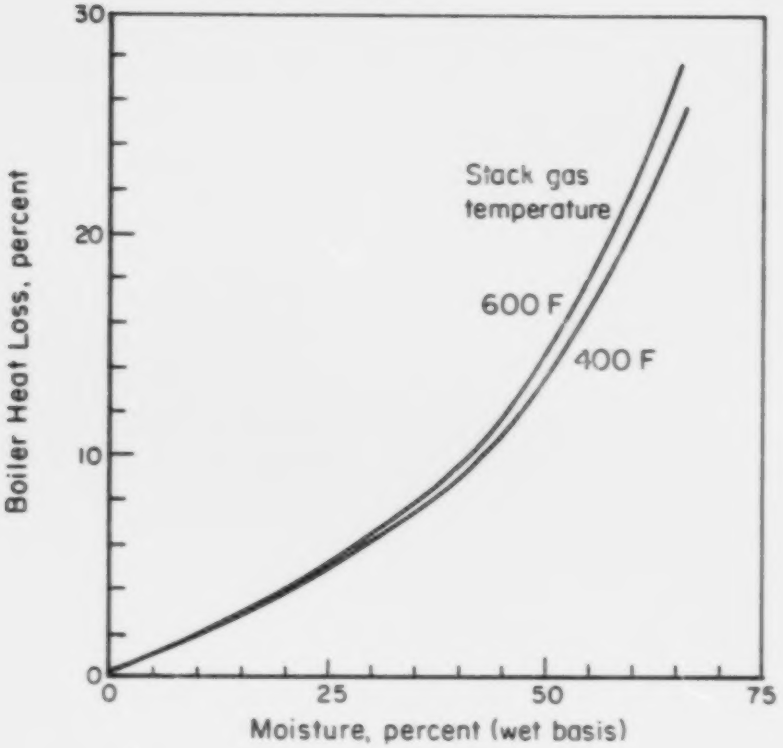

FIGURE 14. BOILER HEAT LOSS VERSUS WOOD MOISTURE CONTENT(9)

TABLE 4. OVERALL BOILER EFFICIENCY AS A FUNCTION OF WOOD MOISTURE CONTENT

Heat Loss Factors	Percent Lost[(a)]		
	5% Moisture	25% Moisture	50% Moisture
Heat loss to dry stack gases[(b)]	9	9	9
Heat loss to moisture in fuel[(c)]	0.5	4	13
Heat loss from formation of moisture from hydrogen in the fuel[(d)]	7-8	7-8	7-8
Heat loss from incomplete combustion[(e)]	4	4	4
Heat loss from radiation and unaccounted for			
	21.5	23	34
Corresponding boiler Efficiency	78.5	75	66

(a) Reference 9, heating loss as a percentage of heating value.
(b) Based on 40% excess air, 400 - 500 F stack gas temperature.
(c) Based on stack gas temperature of 400 - 500 F.
(d) Based on Douglas fir bark fuel.
(e) Assumed.

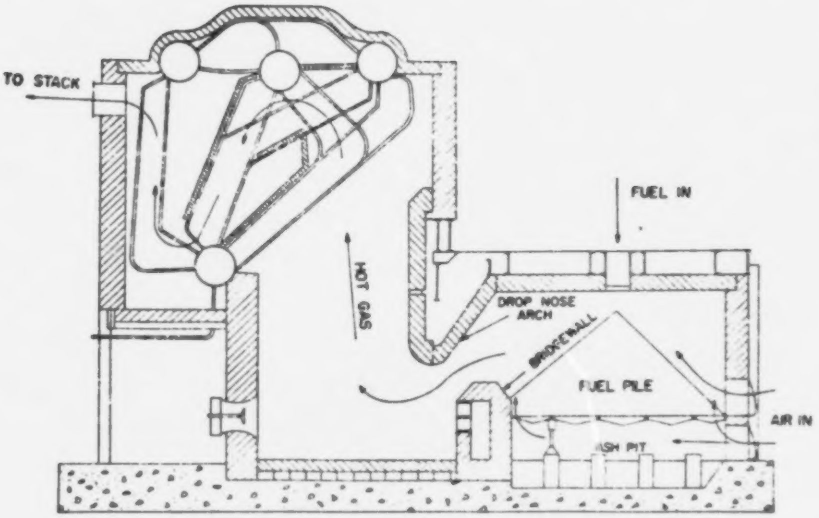
TO STACK
FUEL IN
HOT GAS
DROP NOSE ARCH
BRIDGEWALL
FUEL PILE
AIR IN
ASH PIT

FIGURE 15. BOILER WITH A DUTCH-OVEN FURNACE

Source: Reference 9, Fig. 16, page 13.

fed into the main boiler section where they are further combusted supplying heat to raise steam. The dutch oven partially gasifies or distills the wood and, therefore, can tolerate higher moisture contents than direct combustion. This method, while still in common use, is not extensively employed in modern units today.

Most modern applications of wood firing today utilize various forms of stokers. The most common of these methods is the spreader stoker shown in Figure 16. In this type of an arrangement the hog fuel or wood chips are either flipped or blown into the combustion zone of the boiler where a significant amount of burning takes place in suspension. A typical pneumatic arrangement for blowing wood onto a spreader stoker is shown in Figure 17. The wood that does not burn in suspension falls to some form of grate where the remainder of combustion takes place. Various types of grates can be employed for this purpose. In smaller sizes of boilers, up to about 100,000 lb of steam per hour, stationary or possibly intermittent dumping grates are common. For units larger than this size, traveling grates or self cleaning grates are used almost exclusively. Figure 16 shows the boiler equipped with a traveling grate.

Heat release rates on spreader stoker type operations commonly approach 1,000,000 Btu per hour per square foot of grate area with 35 to 70 excess air and 400 F air temperature(1). Usually, about 80 percent of the combustion air is supplied through the grate and 10 to 20 percent is injected over the grate to stimulate turbulence and mixing in the combustion gases causing more rapid combustion and reduction of smoke emissions.(9) Spreader stoker type boilers can handle wood up to about 55 percent moisture.(8) Moisture contents above 45 percent, however, decrease the combustion rate rapidly.(11) Under these conditions furnace temperature must be maintained above 750 to 1000 F to maintain stable combustion conditions.(1)

The thin fuel bed and rapid burning rates of the spreader stoker result in its being very sensitive to changes in boiler load. Control is necessary over boiler feed rates and air supply rates to maintain stable combustion conditions. The inclined type grate shown in Figure 18, however, characteristically has a deeper fuel bed than a spreader stoker. This large fuel inventory on the grate itself results in its being much less sensitive to load changes.

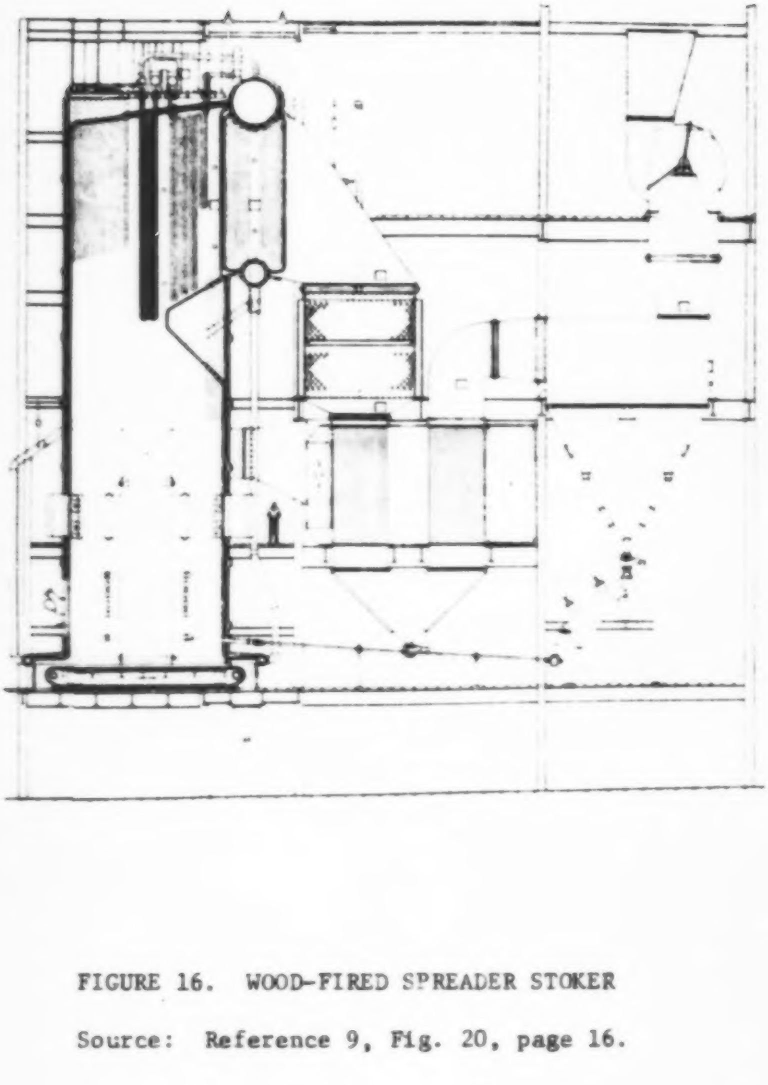

FIGURE 16. WOOD-FIRED SPREADER STOKER

Source: Reference 9, Fig. 20, page 16.

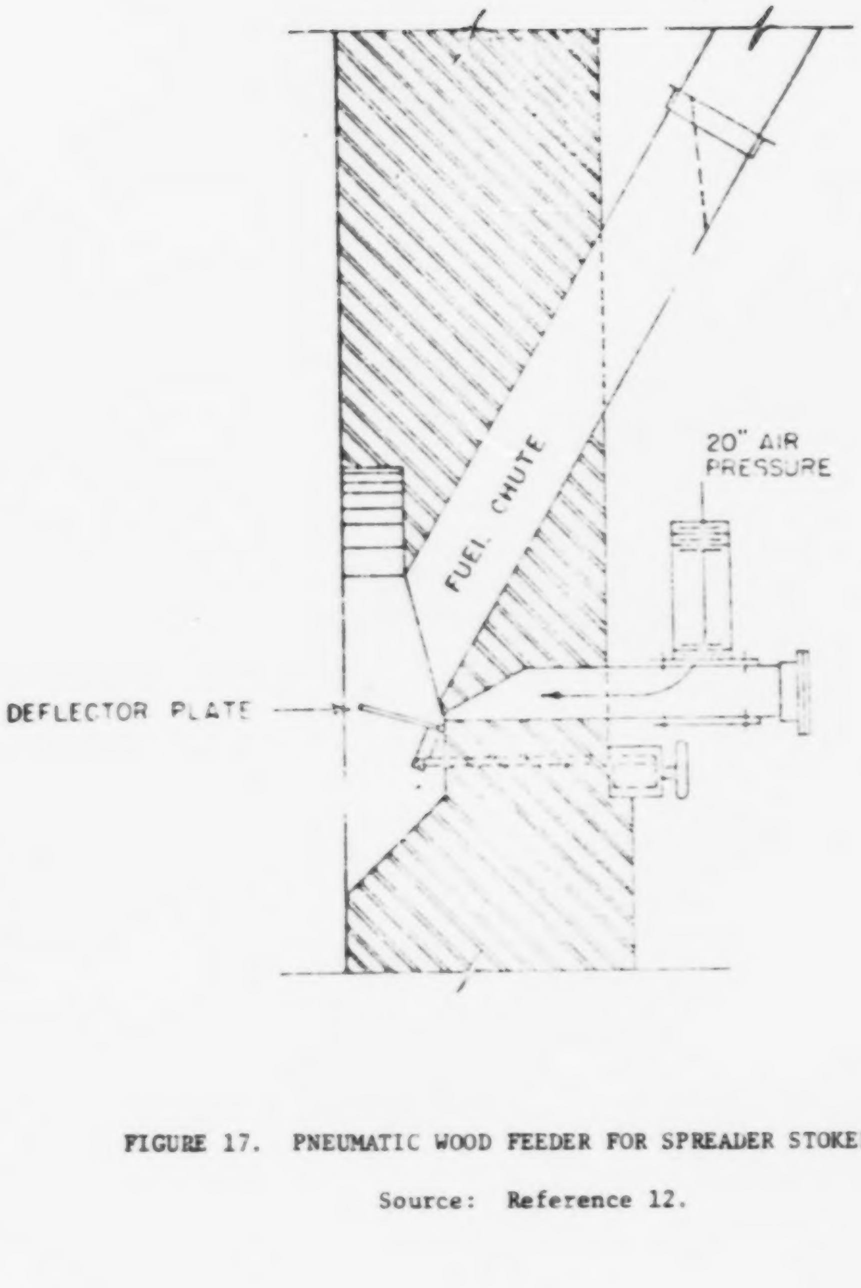
FUEL CHUTE
20" AIR PRESSURE
DEFLECTOR PLATE

FIGURE 17. PNEUMATIC WOOD FEEDER FOR SPREADER STOKER

Source: Reference 12.

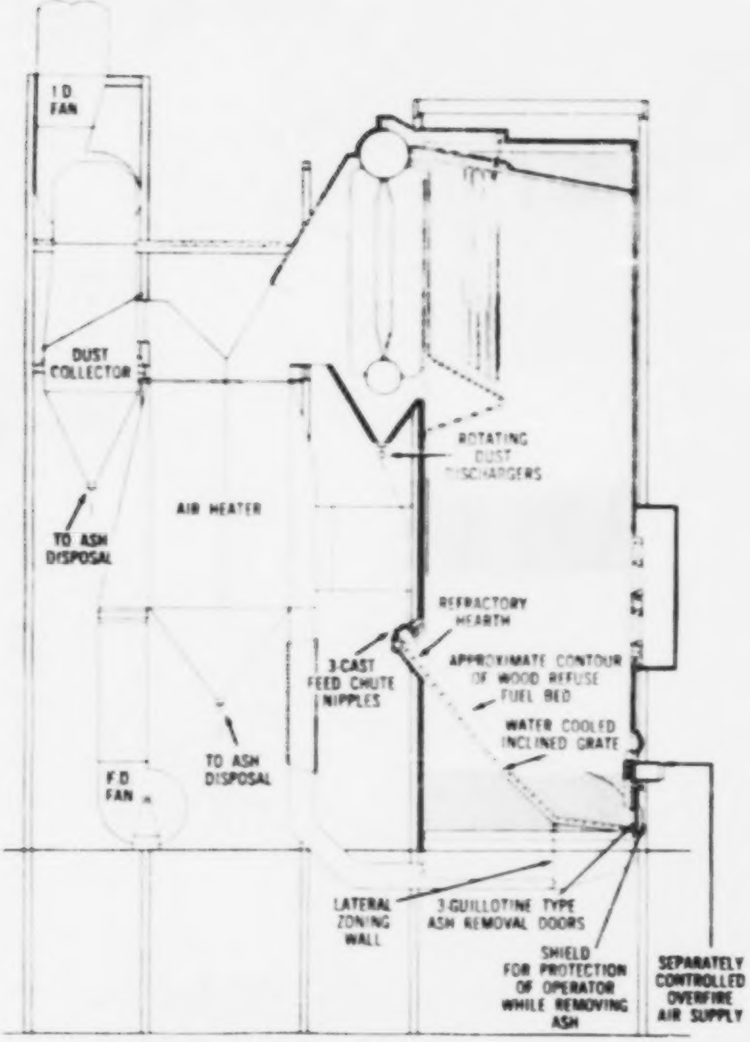
I.D FAN
DUST COLLECTOR
TO ASH DISPOSAL
AIR HEATER
ROTATING DUST DISCHARGERS
REFRACTORY HEARTH
3-CAST FEED CHUTE NIPPLES
APPROXIMATE CONTOUR OF WOOD REFUSE FUEL BED
WATER COOLED INCLINED GRATE
TO ASH DISPOSAL
F.D FAN
LATERAL ZONING WALL
3-GUILLOTINE TYPE ASH REMOVAL DOORS
SHIELD FOR PROTECTION OF OPERATOR WHILE REMOVING ASH
SEPARATELY CONTROLLED OVERFIRE AIR SUPPLY

FIGURE 18. WOOD-FIRED INCLINED GRATE

Source: Reference 9, Fig. 21, page 17.

In all types of stoker applications care must be taken to prevent overheating of the grate in localized areas. Often, the fuel becomes unevenly distributed across the surface of the grate resulting in irregularities in air flow. Overheating occurs in those areas where the air flow is restricted and may cause grate damage. Many times grates are water cooled to alleviate this problem. Careful control of fuel size is also an important factor in preventing grate overheating by lessening the wide variation in fuel density on the grate. Minimizing the amount of slack or material under 1/4-inch diameter that enters in the fuel is most important. Usually, fuel sizes of less than about 1-1/4 to 2 inches with a maximum of 50 percent slack are specified for stoker applications.(13)

Suspension firing of wood is similar to pulverized coal firing. For successful suspension firing wood should be dried as much as possible and reduced to as small a size as possible with a minimum of 50 percent smaller than a 1/4 inch(13). Suspension firing results in a simpler, less expensive boiler than stoker firing, but requires more extensive hogging. It is recommended that an auxiliary fossil fuel, such as oil, natural gas, or pulverized coal, be fired in suspension along with the wood.(13) Normally, wood firing in suspension burning units should not exceed 40 to 50 percent of the total heat input to the boiler, the rest being carried by the auxiliary fossil fuel. A typical suspension fired wood boiler normally has a small dumping type grate installed at the base of the unit to handle excess wood ash or chips which may fall to the bottom without burning.

Cyclone type boilers have seldom been used in wood firing although in Sweden there is currently a cyclone boiler burning wood. The cyclone type burners employed are basically the same as those used for coal as shown in Figure 9. Some coal must be fired along with the wood in order to maintain a slag coating on the outside of the burner. Wood must be also processed to about the same size as required for suspension firing. As mentioned previously, cyclone boilers have been employed less frequently in recent years due to the high propensity for admitting high levels of nitrogen oxides.

Existing Wood-Burning Boilers

The percentages of boiler sales for various fuels in five different capacity categories sold between 1965 and 1973 are shown in Table 5. Though small in sales compared with coal, oil, and natural gas, wood overall ranks as the most significant fuel other than these three major fossil fuels. The vast majority of wood burning boiler sales is in the size range of from 16,000 to 100,000 lbs of steam per hour as shown in Table 6. The type of firing most commonly employed in the different capacity categories is shown in Table 7. The vast majority of boilers sold in the most common size range (16,000 to 20,000 lbs steam per hour) are of either spreader stoker or overfeed stoker design. The category marked "Other" is generally unspecified but probably contains boilers with dutch oven or fuel cell type firing arrangements. In the larger sizes, over 500,000 lbs steam per hour, a few suspension fired units burning coal and wood have been recorded sold in the sales period considered; however, the bulk of sales were with a spreader stoker configuration.

Installed wood burning boiler capacity in the different capacity ranges is shown in Figure 19. Though a relatively few number of boilers were sold over 500,000 lbs of steam per hour the total installed capacity is greatest in this range (the largest unit being 1,700,000 lbs of steam per hour). In many of these units, however, a conventional fossil fuel would normally be fired with the wood carrying a significant portion of the boiler heat load. The most prevalent size range, however, is from about 15,000 lbs per hour to 150,000 lbs per hour.

Some basic conclusions can be drawn from sales of wood burning boilers and other types of boilers in the last ten years.

- As can be seen from Table 5, the vast majority of watertube boiler sales for all fuels for capacities up to 500,000 lbs of steam per hour used natural gas or oil as a primary fuel. Wood is the most significant fuel other than coal, oil, or natural gas.
- The most prevalent size for wood fired boilers is in the range from about 15,000 to 150,000 lbs steam per hour (Figure 19). Some boilers burning fossil fuel plus wood have ben installed in sizes greater than 500,000 lbs steam per hour.

TABLE 5. TOTAL BOILER SALES IN EACH CAPACITY CATEGORY FROM 1965 THROUGH 1973(2). Percent in each capacity range. (a)

(Capacities 10^3 lbs. steam per hour)

FUEL	10-16	16-100	100-250	250-500	over 500
Bituminous Coal	1.9	3.5	6.5	9.4	46.7
Oil	27.1	27.5	31.8	24.9	24.8
Natural Gas	66.9	63.6	48.7	24.2	21.3
Wood bark	0.6	1.6	1.7	1.0	1.3
Other Fuels	3.6	2.9	9.8	35.3	5.4

(a) 10^3 lbs. steam per hour

TABLE 6. WOOD BURNING BOILER SALES IN EACH CAPACITY RANGE FROM 1965 THROUGH 1973(2) (a)

Capacity Range 10^3 lbs. steam/hr	Percent of Boilers Sold In Range
10-16	2.2
16-100	72.8
100-250	18.4
250-500	2.2
Over 500	4.4

(a) Statistics include all boilers with capability for wood firing. In some cases, especially those in the size range over 500 x 10^3 lbs steam per hour, wood may serve as an auxiliary fuel with the bulk of the boiler heat load being carried by conventional fossil fuels.

TABLE 7. WOOD FIRING METHODS FOR DIFFERENT SIZE CATEGORIES FOR BOILERS SOLD BETWEEN 1965 AND 1975[a]

Firing Methods	10-16	16-100	100-250	250-500	Over 500
Spreader Stoker	50.0	34.6	72.5	100.0	66.7
Underfeed Stoker	0	1.9	0	0	0
Overfeed Stoker	0	34.0	20.0	0	0
Suspension	0	0	2.5	0	11.1
Other	50.0	29.5	5.0	0	22.2

(a) Compiled from ABMA data

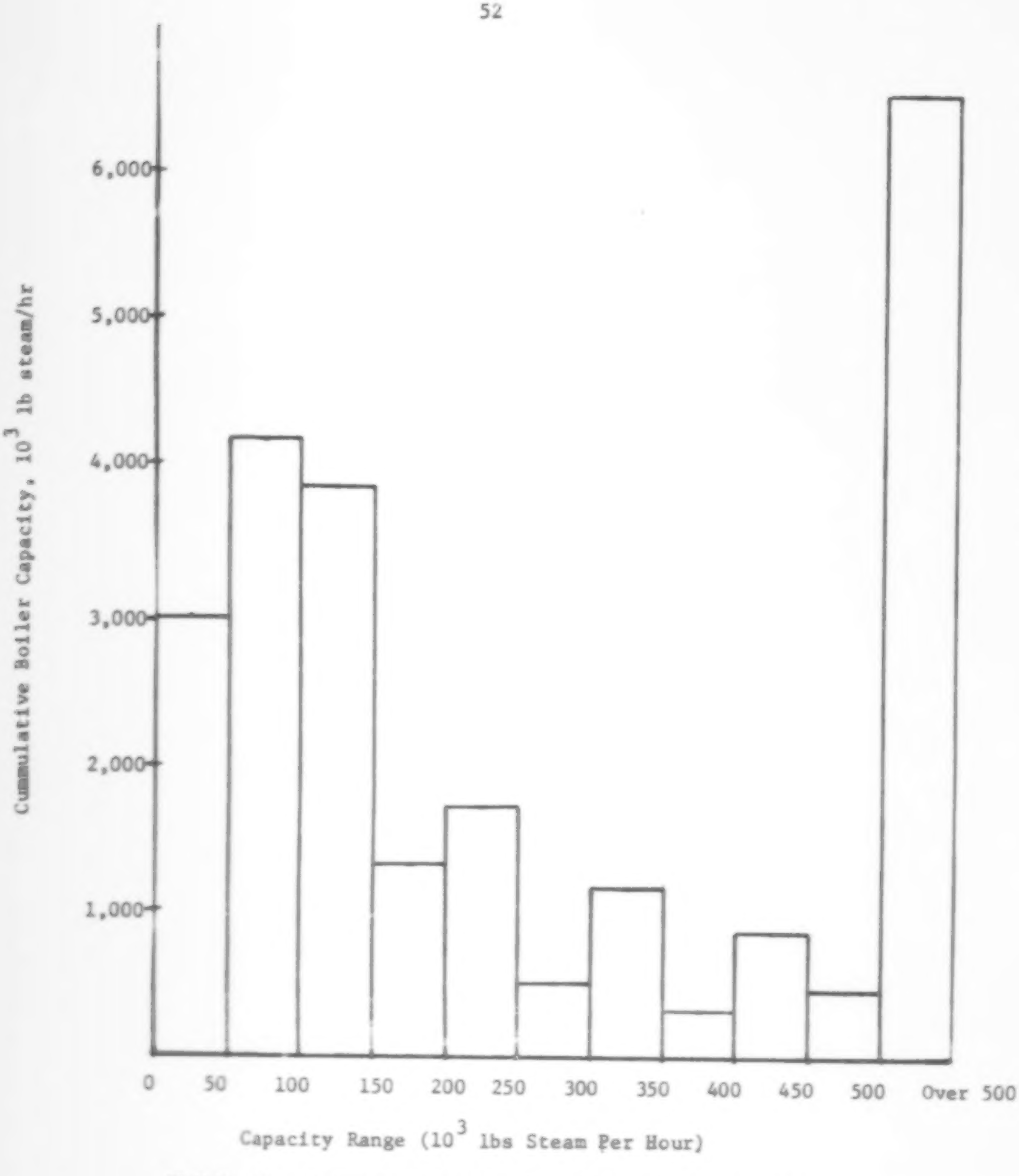

FIGURE 19. CUMULATIVE WOOD BURNING BOILER CAPACITIES IN VARIOUS CAPACITY RANGES SOLD FROM 1965 THROUGH 1975 (ABMA Data)

- The most common firing method for wood fired boilers in all size ranges is the spreader stoker with overfeed stokers also being common in smaller sizes (less than 250,000 lbs steam per hour). Other types of firing such as dutch ovens and fuel cells are also common in smaller sizes. Suspension fired units are not common and those that have been installed are in the larger sizes above 100,000 lbs steam per hour.

Nearly half of wood burning boilers sold between 1965 and 1973 list coal, oil, or natural gas as an alternate fuel(2). The most common alternates are oil and natural gas with coal accounting for only two percent. Some basic considerations are necessary when firing wood in combination with other fuels or substituting wood in boilers designed for other fuels.

A major factor in the design of boiler furnaces is the fraction of total heat released that is absorbed by furnace walls. Usually, about half the heat of combustion is picked up by the furnace wall tubes, the remainder going to the superheater, reheater, economizer, air heater, and the stack. This fraction is important because it establishes the temperature of the gases entering the superheater, thereby determining final steam temperature. Hence any deposits formed in furnace wall tubes decrease heat transfer and lead to higher exit furnace temperature and to higher steam temperature. Great care is taken in designing the furnaces to provide sufficient heat-transfer surface to compensate for wall deposits and to supply wall blowers properly placed to control the amount of deposit that does form.

Natural-gas fired boilers do not have this problem. Boilers fired with residual fuel oil do, but since the ash content of residual fuels generally is less than 0.1 percent, the problem of deposits interfering with heat transfer is usually less troublesome than the corrosive nature of those deposits. With pulverized coal, the problem is very serious since up to about half the ash in the coal may deposit on furnace wall tubes, thereby greatly interfering with heat transfer. Under the worst conditions, heat flux through a coal-ash-slag-covered wall tube may be only a fourth that of a clean tube.

These considerations become important when wood is substituted for fuel oil or coal. Firstly, the ash content of wood is greater than that of residual fuel oil, ranging from about 0.4 percent for redwood bark to a reported 5.3 percent for oak bark$^{(1)}$. Other analyses indicate 2.0 percent ash for birch and 4.3 percent ash for maple$^{(3)}$, indicating roughly that an ash content as high as 5 percent can be anticipated. And, since dry wood has a heating value of 8000 to 9000 btu per pound, the total ash burden in a wood-fired boiler furnace is about comparable to that with a 13,000 btu/lb bituminous coal containing 7 to 8 percent ash. Thus, the fouling potential when burning wood is about comparable on a quantitative basis to that of burning bituminous coal, and much greater - perhaps 50 to 100 times worse - than when burning residual fuel oil.

Qualitatively, wood ash differs radically from coal ash. Although there is no such thing as a "typical" ash analysis, wood ash generally is high in CaO (50-60 percent) and high in Na_2O and K_2O (4-7 percent).$^{(1, 3)}$ Although ASTM cone fusion temperatures are sometimes reported for wood ash, such data are meaningless except in the broadest sense. What is significant is that wood ash is an excellent "flux" for coal ash which is generally high in SiO_2 and Al_2O_3. The viscosity of coal ash slags decreases markedly as CaO increases, reaching a minimum at roughly 50 percent CaO in the slag. Therefore, if wood and coal are burned simultaneously, slagging and fouling might be expected, through the fluxing of the silicates in the coal ash with the CaO in the wood ash.

Further, the alkaline Na_2O and K_2O lead to serious fouling of superheaters in coal-fired boiler furnaces when the alkali level exceeds 0.5 percent of the coal, or about 5 percent alkalies in the ash of a coal containing 10 percent ash. In a wood such as maple with, say, 4 percent ash containing 6 percent alkalies, and allowing for the difference in calorific value, the fouling characteristics would be comparable with badly fouling coals. An additional point here is that the alkalies in wood are probably released in the flame more readily than the alkalies in coal ash, which are generally tied up chemically with minerals such as feldspar or organically as salts of carboxylic acids. If the alkalies in wood are sulfates or chlorides, their action would be more objectionable since this would lead to increased volatilization of alkalies in the flame.

Generally speaking, substituting wood for residual fuel oil will increase problems with fouled heat-receiving surfaces. Burning wood in boiler furnaces designed for pulverized coal likely will not pose fouling problems worse than with coal alone except that alkalies may tend to accumulate more rapidly in the cooler parts of the boiler, such as in the superheater. Burning wood in admixture with coal might be expected to lead to problems with slagging because the principal constituents in wood ash will react readily with the refractory elements in coal ash to form low-viscosity, low-melting-point slags. Such interactions can be predicted with fair success, based on long experience with the fouling and slagging characteristics of coal ash as a function of composition.(14)

The substitution of wood firing in existing coal fired stoker boilers presents the fewest problems. In most cases, only minor modifications to the boiler, such as addition of a wood feeding system or firing ports, would be necessary. Hogged fuel of less than about two inches in size, with a minimum of slack (less than 1/4 inches), should be acceptable to most spreader and overfeed type stokers. Care should be taken, however, in analyzing the effect of the combination of wood and coal ash on the ash fusion temperature to insure that slagging or clinkering does not occur as discussed earlier.

Wood can also be fired in suspension in boilers designed for either pulverized coal or heavy oil. The wood should be reduced in size below about 1/4 inch and dried as much as possible to insure rapid combustion. Most all suspension wood fired boilers have a small grate at the base of the unit to insure complete burnout of any wood chips that do not burn in suspension. Pulverized coal and oil boilers generally do not have such a grate and the addition of one may be necessary, though in firing sawdust or very fine wood with relatively low moisture content such an addition may not be necessary. In the case of some oil fired boilers, soot blowers may have to be added or operated more frequently to allow for the higher ash content of the wood (generally 10 to 20 times that of oil by weight).

Substitution of wood in boilers designed for natural gas or light oil represents a more difficult problem. Generally these boilers are designed with minimum tube spacing and no provision for soot blowers to achieve the least expensive, most compact design. Firing wood in these boilers would require extensive modification and is not considered an attractive application.

In all cases where steady steam conditions are desired, it is advisable to fire an auxiliary fossil fuel such as coal, oil, or gas with the wood limiting the percent heat load carried by the wood. Variations that may occur in wood moisture and heat content would otherwise cause variations in steam conditions. Systems that are most sensitive to changes in fuel composition are those with the minimum amount of fuel in the furnace at any one time. Suspension fired systems are most sensitive and in the past the recommended maximum heat load to be carried by wood was 40 to 50 percent(12). Spreader stokers are less sensitive and overfeed stokers or dutch ovens with thick fuel beds are least sensitive.

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POLLUTANT EMISSIONS AND CONTROL TECHNOLOGY

The environmental aspects of wood combustion are presented in the following paragraphs. Subjects included are: gaseous and particulate boiler emissions, control equipment effectiveness and costs, potential for hazardous organic emissions, and residue disposal problems and by-product uses. In addition, emissions and control technology for fossil-fueled boilers (coal and oil) are included for comparative purposes.

Gaseous and Particulate Boiler Emissions

Emissions to the atmosphere always accompany the combustion of fuel for the generation of steam or electricity. In wood wastes combustion the primary pollutant is particulate matter resulting from the entrainment of ash and sand in the combustion gases. Wood is a relatively low ash fuel compared to coal (see Table 8). Wood, unlike coal or oil, has a negligible quantity of sulfur and sulfur dioxide emissions are therefore very low. Nitrogen oxides emissions are higher relative to coal or oil, according to EPA estimated emissions factors, even though nitrogen content and combustion temperatures are generally lower.

Little emissions data other than particulate emissions have been uncovered in a survey of the available literature. Emission factors provided by the United States EPA for wood and bark combustion in boilers with no ash reinjection or emission controls are presented in Table 9. To obtain the emissions to the atmosphere, the emission factor must be multiplied by the number of tons of wood burned, and, in the case of particulates, reduced by the particulate collector efficiency. A considerable amount of data have been located which specifies dust loading to the collectors, these numbers are quite variable and range from 0.5 to 5.0 grains/scf.(1)*

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* References are listed on page 9

TABLE 8. COMPARATIVE CHEMICAL ANALYSIS OF WOOD AND BARK, COAL, AND OIL

Analyses (dry basis), % by wt	Wood and Bark						Coal			Residual Fuel Oil
	Pine[a] Bark	Oak[a] Bark	Spruce[a] Bark	Redwood[a] Bark	Redwood[b]	Pine[b]	Washed Penn. Coal	Western[d] Coal	Penn.[c] Coal	Range of[e] No. 6 Oil
Proximate										
Volatile matter	72.9	76.0	69.6	72.6	82.5	79.4	35.8	43.4	37.7	
Fixed carbon	24.2	18.7	26.6	27.0	17.3	20.1	57.3	51.7	52.2	
Ash	2.9	5.3	3.8	0.4	0.2	0.5	6.9	4.9	10.1	
Ultimate										
Hydrogen	5.6	5.4	5.7	5.1	5.9	6.3	5.1	6.4	5.0	9.5 - 12.0
Carbon	53.4	49.7	51.8	51.9	53.5	51.8	78.1	54.6	74.2	86.5 - 90.2
Sulfur	0.1	0.1	0.1	0.1	0	0	1.2	0.4	2.1	0.7 - 3.5
Nitrogen	0.1	0.2	0.2	0.1	0.1	0.1	1.6	1.0	1.5	--
Oxygen	37.9	39.3	38.4	42.4	40.3	41.3	7.1	33.8	7.1	--
Ash	2.9	5.3	3.8	0.4	0.2	0.5	6.9	3.3	10.1	0.01 - 0.5
Heating value, Btu/lb	9030	8370	8740	8350	9220	9130	13,970	9,420	13,310	17,410 - 18,990
Ash Analyses, % by wt										
SiO_2	39.0	11.	32.0	14.3				30.7[d]	49.7[d]	
Fe_2O_3	3.0	3.	6.4	3.5				18.9	11.4	
TiO_2	0.2	0.	0.8	0.3				1.1	1.2	
Al_2O_3	14.0	0.	11.0	4.0				19.6	26.8	
Mn_3O_4	Trace	Trace	1.5	0.1				--		
CaO	25.5	64.	25.3	6.0				11.3	4.2	
MgO	6.5	1.	4.1	6.6				3.7	0.8	
Na_2O	1.3	8.	8.0	18.0				2.4	2.9	
K_2O	6.0	0.2	2.4	10.6						
SO_3	0.3	2.0	2.1	7.4				12.2	2.5	
Cl	Trace	Trace	Trace	18.4						

(a) Reference (22).
(b) Reference (11).
(c) Reference (23).
(d) Reference (24).
(e) Reference (22).

TABLE 9. EMISSION FACTORS FOR WOOD AND BARK COMBUSTION IN BOILERS WITH NO REINJECTION[a,b]

Emission Factor Rating: C = Average Accuracy

Pollutant	Emissions, lb/ton
Particulates[c]	25 to 30
Sulfur oxides (SO_2)[d]	0 to 3
Carbon monoxide	2
Hydrocarbons[e]	2
Nitrogen oxides (NO_2)	10

(a) Reference (2).

(b) Approximately 50 percent moisture content.

(c) This number is the atmospheric emission factor without fly ash reinjection. For boilers with reinjection, the particulate loadings reaching the control equipment are 30 to 35 lb/ton (15 to 17.5 kg/MT) fuel with 100 percent reinjection.

(d) Use 0 for most wood and higher values for bark.

(e) Expressed as methane.

Particulate Collection Efficiency

In contrast to coal, where collection efficiency is based on the removal of a given percentage of the very small ash particles (10 microns or less), the basis for hogged-fuel fly ash removal efficiency is specified on the actual material over (larger than) 325 mesh (44 microns) or over 200 mesh (74 microns) collected. The reason for the different basis is the lighter, larger average sized wood fly-ash particles. Figure 20 shows a typical size distribution of fly ash obtained from a bark boiler. Also displayed for comparative purposes is a typical coal fly-ash size distribution. Typical collection efficiencies for high-efficiency multitube cyclone collectors are 93-95 percent for particles over 325 mesh (44 microns), and 95-97 percent for particles over 200 mesh (74 microns).(1)

The emission factors reported in Table 9 are acceptable to calculate gaseous emissions for hogged fuel combustion. However, for particulate matter the reported number is significantly higher than that actually emitted. Assuming a 30 lb particulate/ton emission factor, 93 percent collection efficiency (for particles over 325 mesh) and that 85 percent of the dust loading is over 325 mesh, the effective particulate emission factor is 6.3 lb/ton. On the basis of 45 percent moisture fuel and 8500 Btu/dry lb, this factor can be converted to 0.67 lb/10^6 Btu. The calculated numbers compares well with actual emission test data for combined bark and gas (0.75, 0.76, 0.52 lb/10^6 Btu), bark and oil firing (0.09, 0.15, 0.32 lb/10^6 Btu).(1)

Factors Affecting Particulate Emissions

Some of the reasons for the large range in the published data for particulate emissions from wood-fired boilers include differences in the extent of char reinjection, in boiler type, in grate heat release, in excess air, in wood waste material type (e.g., logs, saw dust, chips) and in wood moisture content. Probably the single most significant factor is the extent of char reinjection utilized. Char reinjection systems, which return collected particles to the combustion zone to achieve more

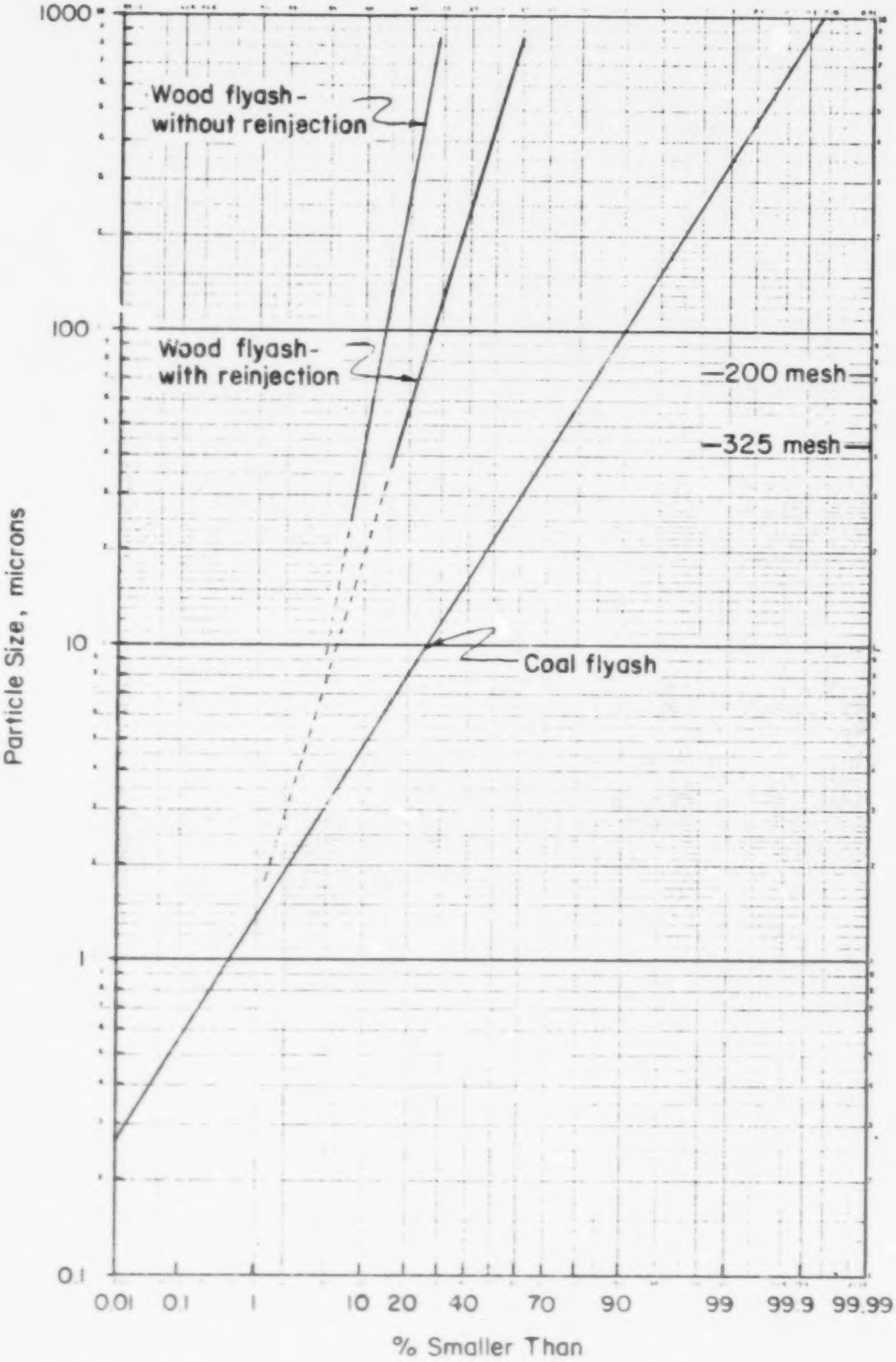


FIGURE 20. SIZE DISTRIBUTION OF WOOD AND COAL FLY ASH(1,20)

complete combustion of the carbon, represent a compromise between two conflicting objectives. While reinjection increases boiler efficiency and minimizes the emission of uncombusted carbon, it also increases boiler maintenance requirements, decreases the average fly-ash particle size (see Figure 20), increases the dust load to the collector, and makes collection more difficult.(3) It has been reported that full injection of collector catch (employed at many paper mills) can easily cause a full 10-fold increase in dust loading to the collector.(1) Properly designed reinjection systems will separate the sand and the char from the exhaust gases, pass the material over separatory screens and reinject the larger carbon fraction to the boiler and reject the fine sand particles to the ash disposal system.

Effectiveness and Costs of Particulate Control Equipment Currently Employed for Wood-Fired Boilers

The effectiveness of air pollution control equipment can be expressed in terms of total emissions per ton fired or in terms of the collection efficiency of a piece of control equipment. Because of the variation in boiler particulate emissions, resulting from ash reinjection rate, boiler type, fuel characteristics, etc., the establishment of a specific dust loading for all cases, is not possible. Data from a leading U.S. dust collector manufacturer indicates that loadings can vary from 0.5 to 3.8 grains/scf.(4) Another source reports loadings in the 0.5 to 5.0 grains/scf range.(1) Because of these variations, calculations of an accurate emission factor is difficult, therefore, collectors must be evaluated in terms of efficiency. High-efficiency multitube cyclone collectors can achieve collection efficiencies in the low to mid-nineties. Currently, the use of multicyclones on hogged fuel boilers provides the sole source of particulate removal for most plants. Costs for multitubular cyclone collectors escalated to mid-1975 (originally reported in 1972) are $133 per 1000 lb steam/hr (15¢/ACFM) and fan power requirements are reported to be 0.9 HP per 1000 lb steam/hr.(5) The variation (in 1968 dollars) in annualized (operating costs plus capital cost amortization) and installed costs, respectively, for low-efficiency (single tube), medium-efficiency (large diameter multitube), and high-efficiency (small diameter multitube) centrifugal collectors are shown in Figures 21 and 22. These costs, although lower than actual mid-1975 costs which are estimated to be approximately 1.6 times the costs shown in the figures, show the wide variation in collector costs as a function of volumetric flow rate and collector efficiency.

Assuming a 96 percent overall collection efficiency, dust loadings cannot exceed 2.5 grains/scf and still meet a 0.1 grain/scf emission regulation (currently the toughest control regulation in the country). Since loadings can range as high as 5 grains/scf, it is clear that additional control equipment may be required to meet the new regulations. Currently, three systems are being employed for secondary control of hogged fuel boiler particulate emissions: (1) two multicyclone collectors in series, (2) multicyclone collector with "shave off system" and scrubber on shave off, and (3) multicyclone collector in series with a low energy scrubber.

Collectors in Series

Employing two collectors in series allows for a first collector to remove the bulk of the dust and a second collector with special high-efficiency vanes for the removal of the finer particles which passed through the first unit. While a two-stage collection system is more efficient than a single-stage system, overall collection efficiency is not likely to exceed 97-98 percent. Costs and fan power requirements are reported to be an additional $140 and 0.5 HP per 1000 lb steam/hr above those for single multitube collector.(5)

Shave Off System

Another alternative for additional particulate control involves a secondary shave off system. The principle involved is shown schematically in Figure 23. The exhaust gases from the collector exit up the outlet tube as a small-radius, high-velocity, spiral which centrifuges the

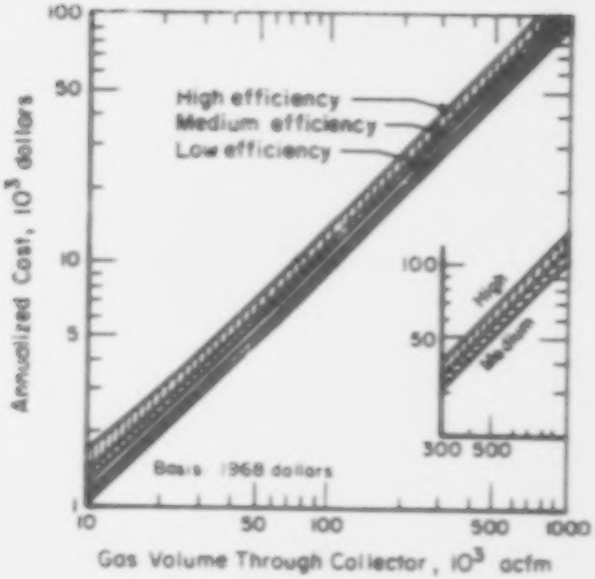


FIGURE 21. ANNUALIZED COST OF OPERATION OF DRY CENTRIFUGAL COLLECTORS

Source: Reference 12.

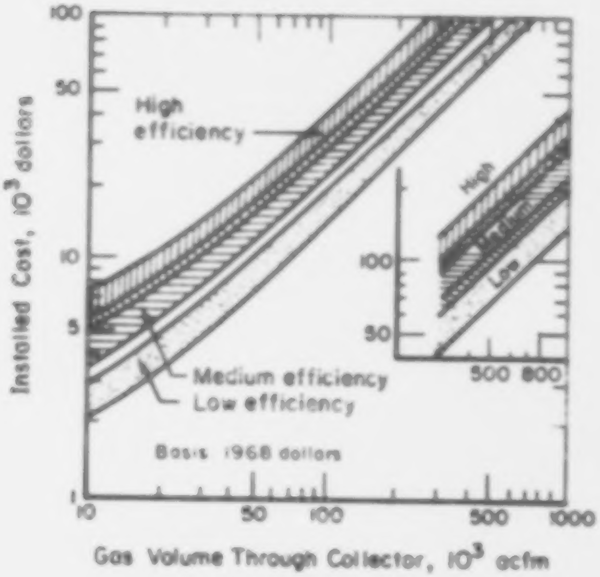


FIGURE 22. INSTALLED COST OF DRY CENTRIFUGAL COLLECTORS

Source: Reference 12.

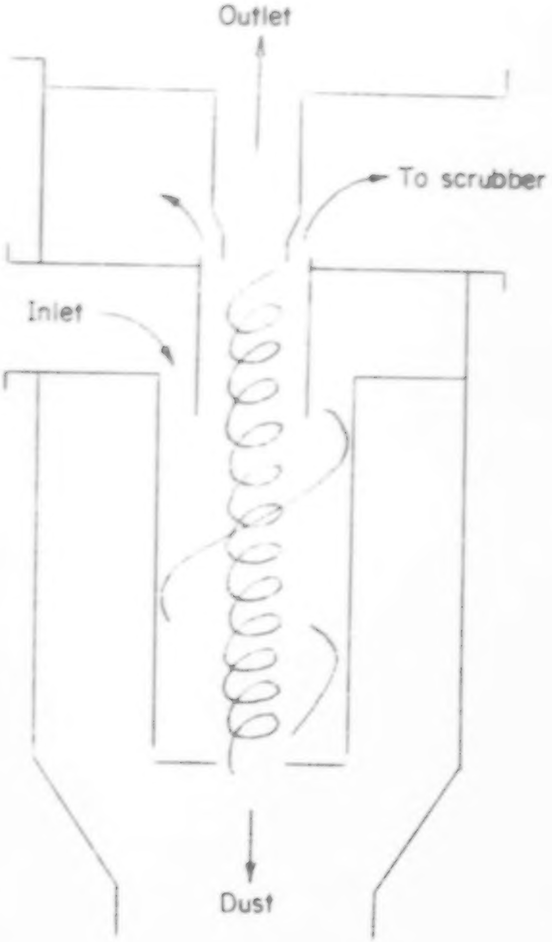

Outlet
To scrubber
Inlet
Dust

FIGURE 23. SECONDARY SHAVE OFF SYSTEM FOR ADDITIONAL PARTICULATE REMOVAL(1)

uncollected dust into the outer boundary area. This outer layer is dust-rich and is separated or "shaved off" from the clean exhaust gases and sent to a low-energy scrubber for final cleaning. No cost data are available for this alternative.(1) Neither the two collectors in series or the the shave off system is thought to have the "potential for continuous efficient dust removal" that a mechanical collector and scrubber in series offers.(6)

Multitube Collector and Scrubber in Series

The best currently available system is a multitube cyclone collector in series with a low energy wet impingement-type scrubber. This system has proven successful in several commercial applications such as the Rosebury Lumber Company in Eugene, Oregon,(6) or the Hoeyner Waldorf Corp. in Missoula, Montana.(7) Equipped with such systems boilers can easily meet emission regulation of 0.1 grains/scf.(6) Costs for this system are an additional $120 (13¢/ACFM) and 1.5 HP per 1000 lb steam/hr over mechanical collection.(5)

Relative Performance and Cost of Alternative Particulate Removal Equipment

Although, at present, the use of multitube-cyclone separators (and in a few locations secondary collection equipment) dominate in particulate control for wood combustion, other collection devices traditionally used for particulate removal could be employed in the future. There is currently available an abundance of information on the relative efficiency of these alternative collection devices. Unfortunately, the available data is not for the collection of wastewood fly ash. However, this data can still be used to calculate the relative performance capabilities of these particulate collectors. Average collection efficiencies are summarized in Table 10 at different partile sizes for various particulate control equipment, e.g., cyclones, electrostatic precipitators, fabric filters (baghouse), scrubbers, etc. Note that, for particles greater than 44 microns, or approximately 85-90 percent

TABLE 10. DISTRIBUTION BY PARTICLE SIZE OF AVERAGE COLLECTION EFFICIENCIES FOR VARIOUS PARTICULATE CONTROL EQUIPMENT[(a)(b)]

Type of collector	Efficiency, %					
		Particle size range, µm				
	Overall	0 to 5	5 to 10	10 to 20	20 to 44	>44
Baffled settling chamber	58.6	7.5	22	43	80	90
Simple cyclone	65.3	12	33	57	82	91
Long-cone cyclone	84.2	40	79	92	95	97
Multiple cyclone (12-in. diameter)	74.2	25	54	74	95	98
Multiple cyclone (6-in. diameter)	93.8	63	95	98	99.5	100
Irrigated long-cone cyclone	91.0	63	93	96	98.5	100
Electrostatic precipitator	97.0	72	94.5	97	99.5	100
Irrigated electrostatic precipitator	99.0	97	99	99.5	100	100
Spray tower	94.5	90	96	98	100	100
Self-induced spray Scrubber	93.6	85	96	98	100	100
Disintegrator scrubber	98.5	93	98	99	100	100
Venturi scrubber	99.5	99	99.5	100	100	100
Wet-impingement scrubber	97.9	96	98.5	99	100	100
Baghouse	99.7	99.5	100	100	100	100

(a) Reference 2.

(b) Data based on standard silica dust with the following particle size and weight distribution:

Particle size range, µm	Percent by weight
0 to 5	20
5 to 10	10
10 to 20	15
20 to 44	20
>44	35

of wood fly ash (see Figure 20), collection efficiency for most of the collectors is approximately 100 percent. The real differences in collection efficiencies are for the smaller particle sizes. Approximately 94 percent of all the wood fly ash particles are larger than 10 microns and 96 percent are larger than 5 microns (extrapolation). Employing this distribution of particle sizes and the reported efficiencies in Table 10, the calculated collection efficiencies for wood fly ash are presented in Table 11 for cyclones, multiple cyclones (6 in. diameter), electrostatic precipitators, wet-impingement scrubbers, venturi scrubbers, and fabric filters. Annualized and installed costs (1968 dollars) for cyclone separators were presented in Figures 21 and 22. Annualized and installed costs (1968 dollars) are presented graphically for wet scrubbers (Figures 24 and 25), for electrostatic precipitators (Figures 26 and 27), and for fabric filters (Figures 28 and 29).

With the available cost information assembled, and on the basis of 500,000 lb steam/hr or 316-440 x 10^3 ACFM (calculated from Table 14 in Reference 8, based on twice the average flow rate), particulate control costs for a 50 MWe power plant were calculated. Installed and annualized costs for cyclones, wet scrubbers, fabric filters, and electrostatic precipitators are presented in Table 12. The installed costs given are for the collector alone. The required fan, ducting, and other installation costs will increase the total cost of the installed collector. The large range in the numbers presented for each collector reflect both the large variability in actual control costs and the fact that all the data presented are not on the same basis (numbers in parentheses are on different bases, which are identified in appropriate footnotes). While there is significant variability in the cost data, the relative position (in terms of lowest cost control method) of the alternative control methods can be assessed. It can be concluded from Table 12 that of the control methods capable of achieving <0.1 grain/scf particulate emissions, the cyclone-scrubber system and electrostatic precipitator collectors are the two most economical control systems.

As noted earlier, the use of multicyclone collectors alone will not be sufficient to meet new emission limits of <0.1 grain/scf,

TABLE 11. CALCULATED WOOD ASH COLLECTION EFFICIENCIES FOR VARIOUS CONTROL EQUIPMENT

Type of Collector	Efficiency[(a)], %
Long-cone cyclones	94.2
Multiple cyclone (6-in. dia)	98.4
Electrostatic precipitator	99.7
Wet-impingement scrubber	99.8
Venturi scrubber	99.96
Fabric filter	99.98

(a) Based on efficiencies per particle size reported in Table 10, and the following size distribution.

Particle size range, microns	Percent by weight
0 to 5	4
5 to 10	2
20 to 10	2
20 to 44	2
>44	90

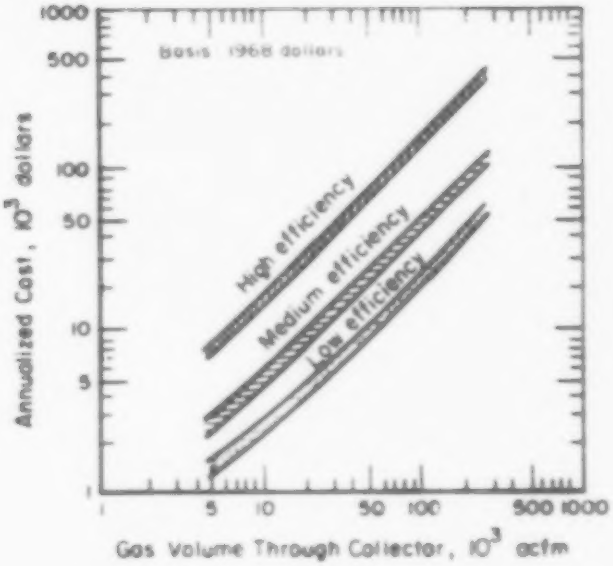


FIGURE 24. ANNUALIZED COST OF OPERATION OF WET COLLECTORS

Source: Reference 12.

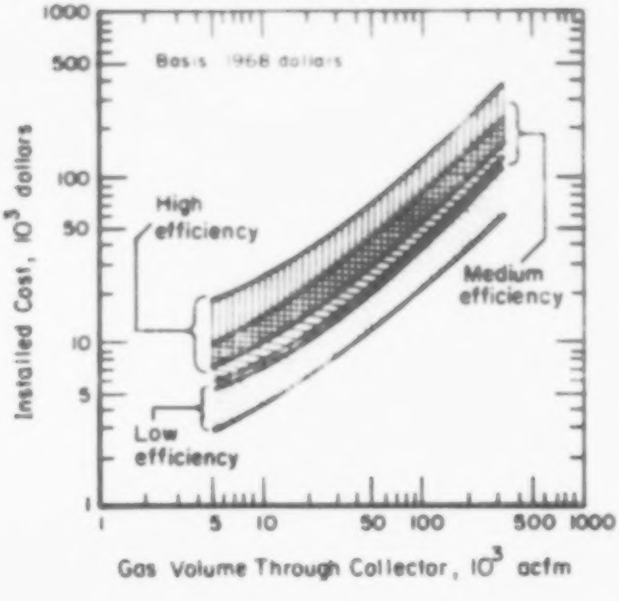


FIGURE 25. INSTALLED COST OF WET COLLECTORS

Source: Reference 12.

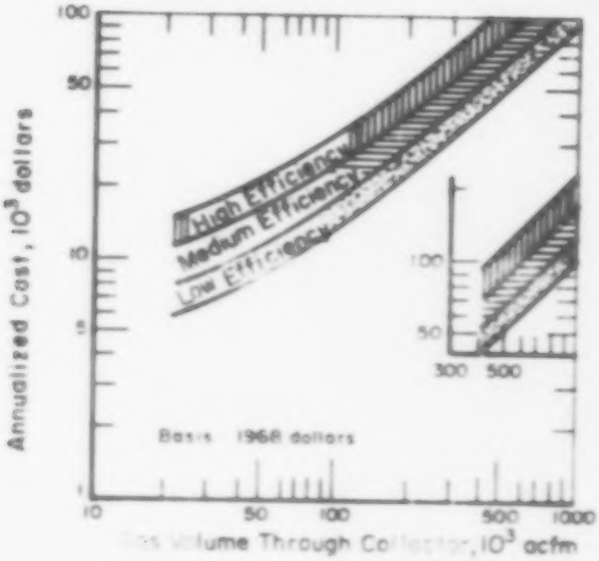


FIGURE 26. ANNUALIZED COST OF OPERATION OF HIGH-VOLTAGE ELECTROSTATIC PRECIPITATORS

Source: Reference 12.

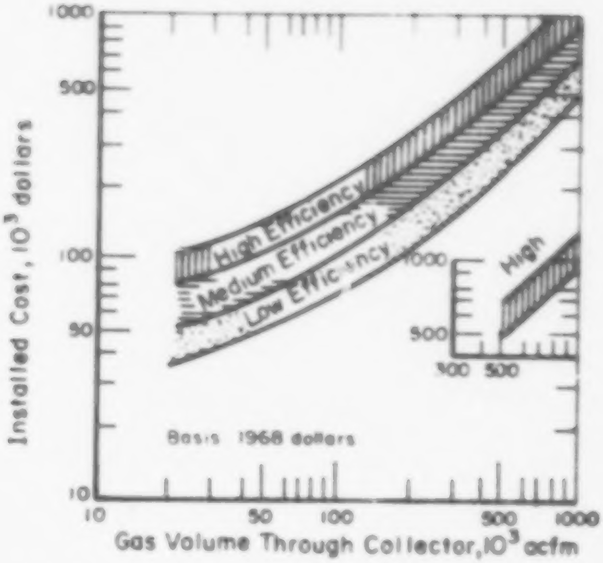
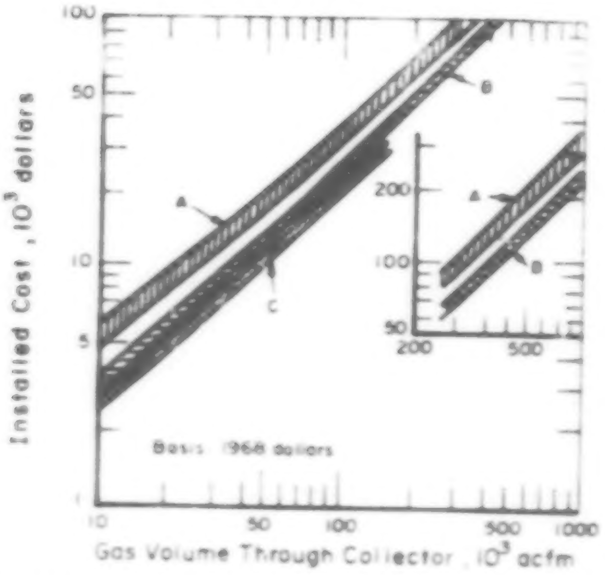


FIGURE 27. INSTALLED COST OF HIGH-VOLTAGE ELECTROSTATIC PRECIPITATORS

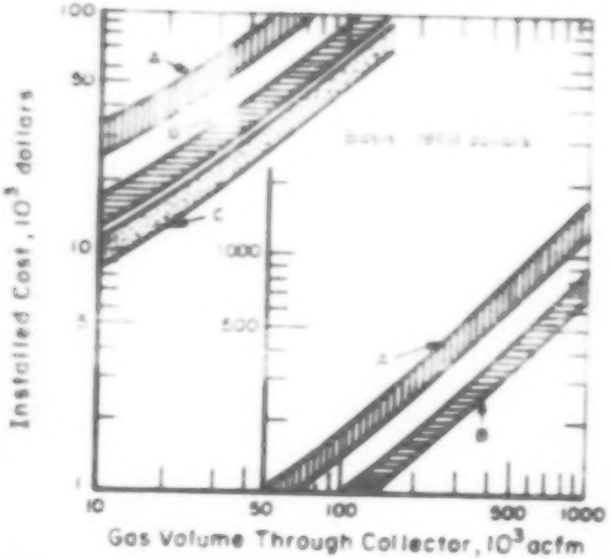
Source: Reference 12.



(a) High-temperature synthetics, woven and felt. Continuous automatic cleaning.
(b) Medium-temperature synthetics, woven and felt. Continuous automatic cleaning.
(c) Woven natural fibers. Intermittently cleaned - single compartment.

FIGURE 28. ANNUALIZED COST OF OPERATION OF FABRIC FILTERS

Source: Reference 12.



(a) High-temperature synthetics, woven and felt. Continuous automatic cleaning.
(b) Medium-temperature synthetics, woven and felt. Continuous automatic cleaning.
(c) Woven natural fibers. Intermittently cleaned - single compartment.

FIGURE 29. INSTALLED COST OF FABRIC FILTERS

Source: Reference 12.

TABLE 12. PARTICULATE COLLECTOR COSTS FOR A 50 MWe COAL- OR WOOD-FIRED POWER PLANT(a)

Collector Equipment	Installed Cost, $1000	Annualized Cost, $1000
Cyclone - high efficiency	192 - 288 (66.5)(b)	72 - 99
Cyclone with low energy scrubber in series	422 - 633(c) (258.5)(e)	192 - 264(d)
Wet scrubbing - high efficiency	480 - 752 (1500)(f) (333)(h)	800 - 1040 (130)(g) (351)(i)
Electrostatic precipitator	672 - 848 (692)(j)	112 - 144 (130)(k)
Fabric filter (baghouse)	752 - 1040 (1000)(l)	240 - 288 (17.5)(m)

(a) Basis: 316-440 x 10^3 ACFM, and Tables from Reference 12 presented in the text unless otherwise noted. All costs adjusted to mid-1975 dollars. Costs of fans, ducting, etc., are not included.

(b) Purchase cost basis from Reference 5: $133/1000 lb steam/hr. At 500,000 lb steam/hr this is equivalent to $66,500.

(c) Calculated installed cost based on the high efficiency cyclone costs presented, and the information obtained from Reference 5, that cyclone-scrubber systems are approximately 120 percent greater than cyclone system alone.

(d) Calculated annualized cost based on cyclone annualized costs and the estimate that cyclone-scrubber systems costs are approximately 167 percent greater than cyclones alone, Reference 5.

(e) No data available in terms of installed costs, but from Reference 5, purchase cost basis is $192/1000 lb steam/hr addition to cyclone costs - or a total of $258,500.

(f) Investment cost rate from Reference 17 is $30/kw.

(g) Operating cost rate from Reference 17 is $2.6/kw/yr.

(h) Capital cost for collector from Reference 31.

(i) Annualized cost for collector from Reference 31.

(j) Capital cost for collector from Reference 31.

(k) Annualized cost for collector from Reference 31.

(l) Investment cost rate from Reference 17 is $20/kw.

(m) Operating cost rate from Reference 17 is $0.35/kw/yr.

unless the inlet dust loading can be held to 2.5 grains/scf or less. The three alternative control options capable of solving the problem: (1) fabric filters, (2) electrostatic precipitators, and (3) wet scrubbers, are discussed below.(5,6)

> Fabric Filters: High capital and operating costs, large size, and prone to fire hazards. (Some vendors claim that the fire hazard can now be eliminated.) Highest collection efficiency.
>
> Electrostatic Precipitator: High capital and operating costs, large size, and no proven performance on waste wood boilers. High collection efficiency.
>
> Wet Scrubber-High Energy: Moderate capital costs but high power requirements resulting in high operating costs. High collection efficiency and large quantities of scrubber sludge produced.
>
> Wet Scrubber-Low Energy: Relatively low capital costs, reasonable operating costs, sufficiently high collection efficiency, ease of maintenance, proven performance, and low generation of concentrated scrubber sludge.

In conclusion, of these alternative collection routes, the most promising and the one being employed in new installations is the low energy impingement-type scrubber connected in series with a multitube-cyclone separator.

Emission of Potentially Hazardous Organic Compounds

No specific data on the types of organic compounds emitted from hogged fuel combustion was found in a search of the literature. However, data for a similar emission source, i.e., broadcast fire of forest slash (branches and other residues left after cutting timer), show that most components appear to be low molecular weight hydrocarbons and alcohols. Acetone and simple aromatic compounds along with several short chain unsaturated compounds (olefins) also are present. The estimated rate of hydrocarbon emissions was reported in Table 9 as 2 lb/ton; however, investigation of the basis for this number shows that it was not derived from actual emission tests from hogged fueled boilers. Additional review of the literature by researchers in Oregon has shown that 4 lb/ton may be a more realistic number, and that emissions as high as 55-85 lb/ton have been reported for wood waste boilers under conditions of very poor combustion.(9) During these periods of high hydrocarbon emissions, potentially hazardous organic compounds such as carcinogenic compounds and/or photochemically active compounds could be emitted.

Carcinogenic Compounds

Review of the available data and consultation with those knowledgeable in the field indicate that very little direct information on the carcinogenic nature of emission from wood waste combustion exists. However, it is known that the production of various high boiling organic compounds from the combustion of solid fuels such as coal are carcinogenic.(10) In addition, it is believed (because of the simularity between coal and wood) that emissions of similar chemicals could result from waste wood combustion. However, these emission should be in lower concentrations. At present there are a number of organic compounds arising from the combustion of solid fuels which are known or suspect carcinogens. As a first approximation, these compounds can be limited to some of the compounds with boiling points in the 250 C and higher range. This includes polycyclic and methylated derivatives of polycyclic hydrocarbons, and nitrogen (hetrocyclic) compounds.(13)

Because evidence for carcinogenity must be based on reports of occupational exposure, epidemiological observations and extrapolations of laboratory studies, only a few of the hundreds of compounds produced in solid fuel conversion have been adequately investigated. Therefore, many other chemicals emitted from the combustion process may be hazardous.

In conclusion, there appears to be evidence that carcinogenic compounds may be emitted, but in a very low concentrations, from the combustion of wood. While no detailed information is available, it can be assumed that production of these compounds will be proportional, if not directly related to, the degree of incompleteness of the combustion process. In comparison with the most abundant alternative fuel source, coal, emission of carcinogenic compounds from the combustion of wood is estimated to be less than that from a correspondingly sized coal-fired power plant.

Photochemically Active Compounds

Other hazardous organic compounds which could be emitted from wood waste boiler during periods of poor combustion are photochemically active compounds. It has already been stated that hydrocarbon emissions, during extremely poor combustion periods, can rise to twenty to forty times the normal emission rate. It is possible under these conditions that some of the hydrocarbons could react in the presence of sunlight to form highly reactive peroxy compounds. These peroxy compounds interfere with the normal nitrogen-oxygen photochemical cycle by oxidizing nitric oxide to nitrogen dioxide, thereby preventing the destruction of ozone (which is normally consumed in the oxidation of nitric oxide to nitrogen dioxide) and allowing it to accumulate in higher than normal concentration. This excess ozone concentration is a prime factor in the complex phenomena called photochemical smog.(15)

Unsaturated hydrocarbons are generally the most photochemically active compounds. Fortunately olefins containing fewer than four carbon atoms, like the compounds reported to be produced from combustion of materials similar to wood, are much less reactive. The compounds showing the greatest activity are multisubstituted aromatics and branch chained olefins. While these compounds have not as yet been identified in wood boiler emissions, there is evidence that such compounds exist in the wood and bark itself, and could be emitted during periods of poor combustion.(16) Tunge and Kwan note in their paper that an unpublished EPA report on wood waste emissions states that "forest fires and the burning of agricultural wastes (a system where emissions should be similar to wood burning under poor combustion conditions) produce hydrocarbons of which approximately 11 percent are considered reactive.(9)

Therefore, information presented leads to the conclusions that photochemically active hydrocarbons will probably be emitted in low quantities during periods of poor combustion. If NO_x concentrations are sufficiently high this could lead to the formation of small quantities of photochemical smog. However, the information does not suggest that photochemical smog formation resulting from the combustion of waste wood for the generation of electricity, especially when operated in compliance with existing air pollution control regulation, is anticipated to be a problem.

Solid Residues From Burning Wood

Combustion of hogged fuel transforms wood's complex mixture of cellulose, lignin, oils, resins, and other organic and inorganic compounds into carbon dioxide, water, incompletely combusted char and ash. Residues from the combustions process consist of boiler ash, clinker and slag, and fly ash and carbon char. These residues are normally collected, mixed together, and disposed.

Residue Characterization

Wood fly ash, once it has been collected from the combustion gases, has not received a great deal of attention in the technical literature. Boiler ash, clinker, and slag have also been neglected except as their fusion temperature affects boiler design. Therefore, technical information on boiler residues are somwhat limited. In addition to the ash analyses presented in Table 8 the analysis of boiler ash from an approximately 70 percent bark-30 percent wood fuel burned in the Eugene, Oregon, power plant is presented in Table 13. As expected, the major components are inert silicon (silica) and aluminum (alumina) oxides. Because of the similarities of the elemental analysis of wood, regardless of species or location (as noted in Table 8), the ash composition from wood combusted in Vermont should be similar to the analysis in Tables 8 and 13. The wood ash can be characterized as a relative inert powdery solid with a minor fraction of sodium, magnesium, and potassium along with trace amounts of heavy metals.

TABLE 13. SPECTROGRAPHIC ANALYSIS OF HOGGED FUEL ASH[(a)]

Components	Concentration, ppm
Silicon (Si)	19.6
Aluminum (Al)	3.6
Calcium (Ca)	2.9
Sodium (Na)	2.1
Magnesium (Mg)	0.8
Potassium (K)	0.3
Titanium (Ti)	0.1
Manganese (Mn)	0.016
Zirconium (Zr)	0.006
Lead (Pb)	0.003
Barium (Ba)	0.010
Strontium (Sr)	0.002
Boron (B)	0.003
Chromium (Cr)	Less than 0.001
Vanadium (V)	Less than 0.001
Copper (Cu)	Less than 0.001
Nickel (Ni)	Less than 0.001
Mercury	Nil
Radioactivity	Nil

(a) Reference 18.

Disposal Problems or By-Product Uses

No disposal problems have been identified for the disposal of wood boiler ash or fly ash. The normal procedure is to either transport the collected ash to a sanitary landfill or dump for disposal, or slurry the ash for disposal in lagoons. Analysis of the ash (Tables 8 and 13) shows that the wood residues to be composed primarily of inert silica and alumina. Disposal of this material in a safe and environmentally acceptable manner should not require any special provisions.

Information on by-product uses for wood ash is at this time limited. While several sources briefly mention the possibility of employing boiler ash as a soil conditioner, no detailed information has been presented. A test program was initiated in 1973 in Eugene, Oregon, to use the boiler ash from a wood-fired power plant as a soil conditioner.(18) A check on the progress of this program in August, 1975, showed that because of poor participation (the farmers wanted the ash delivered to their farms) only about 40 tons had been distributed. Consequently, very little useful data have been obtained.

In Eugene, the soil conditioning value of the boiler ash is twofold: (1) The ash helps "break up" the heavy clay soil, adding permeability, and making the soil more manageable, and (2) the alkaline ash helps raise the pH in the acidic soils to a more acceptable growth promoting level.(19)

In addition, there does appear to be some basis, because of the similarity in the inorganic composition of bark and wood ash, for the claims of boiler ash as a nutrient supplement. A considerable amount of work has been done on the use of bark as a fertilizer and soil conditioner. Howard reports in his review article that analyses showed that, "except for nitrogen, the bark (both hardwoods and softwoods) had all the necessary inorganic constituents of a first-class organic soil. There is ample calcium, magnesium, phosphorus and potassium."(21) These same constituents are available in wood ash. Like bark, the fertilizer value of wood ash would be increased by supplementing with extra nitrogen, and depending on the plant crop to be grown, phosphorus, potassium and trace elements. There appears, then, to be a reasonable potential that wood ash could be successfully employed as a soil nutrient and conditioner.

Another potential use of wood ash residues is the carbon cinders recovered in the fly ash collectors. These materials can either be reinjected into the boiler or collected and sold for use in charcoal briquet manufacture.(5)

A final use of wood ash residues noted in the literature is as a spontaneous combustion preventative. The fly ash slurry coming from the particulate removal scrubbers is combined with the sand and char from the cyclone collectors to form a pasty mix. The sludge formed can be easily disposed or employed as a combustion retardant.(5)

Emission Control Technology for Fossil-Fuel Boilers

Included in this section are summaries of currently available technology for the control of nitrogen oxides (NO_x), sulfur oxides (SO_2), and particulate emissions from coal and oil-fired power generation. This material is presented to allow more comparative evaluation of the environmental aspects of coal, oil, and wood combustion.

Nitrogen Oxides

Nitric oxide (NO) and nitrogen dioxide (NO_2), commonly referred to as NO_x, are important in the formation of smog. Nitrogen oxides in the atmosphere come primarily from the internal combustion engine but a significant fraction also is produced in power generation.(25) The formation of NO_x results primarily from the high temperature oxidation of atmospheric nitrogen in the combustion process. In addition, a smaller but significant fraction comes from the oxidation of the chemically bound nitrogen in the fuel.

High concentrations of NO_x are considered harmful to plants, animals, and humans, and in some cases corrosive to fibers and metals. However, because the ambient concentration of NO_x in most locations is low, there does not appear to be a need for absolute or uniform control of NO_x from electric power stations throughout the country. Presently, Los Angeles and Chicago are the only two cities requiring such control to meet ambient air quality requirements set by the Federal Government. In a low population density area such as Vermont, NO_x controls should probably not be required. Should such requirements be set by the State or become necessary to meet Federal ambient air quality requirements the present state of the art calls for modification of the combustion process, rather than use of collectors or scrubbers employed for other types of atmospheric pollutants.

Four NO_x control techniques (other than fuel substitution) are possible for reduction of emissions from either coal fired dry-bottom type furnaces (wet bottom boilers will require retrofitting to dry bottom type prior to control) or oil-fired boilers. The four methods are as follows:

(1) Low (or minimum) excess air firing
(2) Staged combustion and off-stoichiometric firing
(3) Flue-gas recirculation
(4) Water injection.

In the first technique, the quantity of air above stoichiometric requirements admitted to the boiler is kept to an absolute minimum; NO_x reductions as high as 50 percent have been experienced. Staged combustion and off-stoichiometric firing involve running some or all the burners rich in fuel, then introducing the balance of the air through special ports or through fuel-lean burners. NO_x reductions as high as 60 percent are possible with these techniques. Flue gas recirculation involves recirculating a portion of the coal combustion products back to the firing chamber. Little data are available for this technique in large-scale boilers, but NO_x reductions similar to the other techniques are anticipated. A much less promising technique, compared to the other methods, is water injection. In this control method the injected water reduces flame temperature and consequently NO_x formation. Unfortunately, the lower temperature also results in a significantly lower thermal efficiency.

The technology for NO_x removal is in its early stage of development. Significant new developments can be anticipated in the future. The technology to efficiently reduce NO_x emissions (i.e., without unduly affecting boiler operation) from all power plants is not currently available. The two most suitable methods to date for NO_x control in coal- or oil-fired boilers are staged combustion and off-stoichiometric firing. Reductions as high as 60 percent are possible without significantly derating (lowering the output efficiency) the boiler.

Sulfur Dioxide

Although all the pollutants discharged to the atmosphere contribute to the pollution hazard, sulfur dioxide is considered by health authorities to pose the single most serious threat. Sulfur oxides pose serious health effects to man, animals, and vegetation, and are corrosive to materials and structures. Their odor can have detrimental effects, both physiologically and psychologically. Because of the seriousness of the problem, the Federal Government has set, in addition to ambient-air-quality standards, new source performance standards for a number of industrial activities including fossil-fueled power plants. To meet the 1.2 lb $SO_2/10^6$ Btu standard, efficient and unfortunately costly SO_2 control techniques will be required. The primary means to reduce SO_2 emissions are as follows:

(1) Fuel substitution
(2) Stack gas cleanup
(3) Physical cleaning of high pyritic sulfur coals.

Fuel Substitution. The use of an alternative fuel lower in sulfur content has in the recent past been the most acceptable, lowest cost method to reduce SO_2 emissions, i.e., natural gas or oil substitution for high sulfur coal. However, with the growing depletion of domestic supplies of natural gas and oil, and the recent dramatic increases in fuel oil costs, this option is no longer economically viable. In light of these events, the use of coal is anticipated to increase substantially in the near future. The only economical sources of low sulfur coal is Western coal (low sulfur Eastern coal is reserved primarily for metallurgical purposes). However, for Eastern utilities such as in Vermont, the cost to transport low sulfur Western coal will likely make this option economically unattractive (at least compared to stack gas cleanup). Another alternative fuel option not normally considered is the use of waste wood to generate power.

Stack Gas Cleanup. Assuming that high sulfur coal or residual oil is employed to generate power, the remaining SO_2 control method is stack gas cleanup. There is a continually growing number of companies offering stack gas cleanup processes; however, they are basically all very similar. In these processes the flue gases containing the SO_2 are first cleaned of particulates, then set to a contracting device where an aqueous-alkali solution and the flue gases are intimately mixed. In regenerative-type processes, the SO_2 is recovered from the absorbing media and converted to elemental sulfur or sulfuric acid while the absorbing media is regenerated and recycled. In throwaway processes, the SO_2 is reacted with the alkali to form a slurry of insoluble sulfates or sulfites of calcium which is pumped to a holding lagoon to be dewatered. The large quantities of quick-sand-like scrubber sludge produced is currently the major problem with throwaway processes.

The most commercially successful stack gas cleanup processes have been of the throwaway type. The three most prominent are lime (calcium oxide) scrubbing, limestone (calcium carbonate) scrubbing, and double alkali (calcium oxide and soda ash) scrubbing. The principal reasons for their successes over regenerative processes have been their lower capital requirements and greater reliability. The three most prominent of the regenerative processes are magnesia scrubbing (with thermal regeneration), sodium sulfite scrubbing (with steam stripping regeneration), and catalytic oxidation (of SO_2 to SO_3) and absorption in dilute sulfuric acid. All the processes noted above are capable of reducing SO_2 emissions by at least 80 to 85 percent.(17)

The state-of-the-art of stack gas scrubbing is still rapdily changing. While the United States EPA has concluded that the stack gas cleaning is an efficient and sufficiently reliable control technology(26) many feel that no stack gas cleanup process has been sufficiently developed and tested to guarantee acceptable performance. Because of these reservations, and the fact that scrubbing systems are still in the demonstration and development stage, new, lower cost, more efficient processes can be anticipated to be developed in the future.

Physical Cleaning. The sulfur content of high sulfur Eastern coals is composed of an inorganic (or pyritic) and an organic fraction. The organic fraction is chemically bound into the structure of the coal and cannot easily be removed. The pyritic fraction, often comprising a significant part of the total sulfur content, can be removed by washing or physically cleaning the coal. In most cases, the coal's sulfur content can be reduced by at least one-third by this method. A recent study indicates that approximately 25 percent of eastern bituminous coals are either naturally occurring low-sulfur coals or can be washed to 1.2 lb $SO_2/10^6$ Btu with a Btu recovery of 90 percent. Blending with a low-sulfur fuel such as Western coal, municipal refuse, or wood could allow an even greater percentage of the physically cleaned coals to meet the SO_2 emission regulation.(17)

Particulates

Particulate emissions are the most visible, and, therefore, the most controlled, atmospheric pollutant. Particulate control is required for all coal-fired units; fuel oil-fired boilers burning some residual oils may also require controls. Control equipment for particulate removal are either of the wet or dry type.

Wet type collections are scrubbing devices where the flue gas and water are intimately mixed. The resultant slurry is clarified for solids removal, neutralized, and the water recycled; the gas is reheated (to increase buoyancy) and exhausted to the stack. Collection efficiencies as high as 99.9 percent are possible.

Dry type collectors can be classified as either mechanical or electrostatic. Mechanical collectors include cyclones and fabric filters (baghouses). In cyclones the solid particles are separated from the gas stream by the centrifugal action on the gas created inside the device. Cyclones are normally employed to remove the large particles from the gas steam prior to entering a more efficient collector. Collection efficiencies of cyclones are normally low, around 80 percent, but can be increased by using longer, smaller diameter tubes such as in multitubual cyclone collectors. Fabric filters are another mechanical dry collector. The flue gas is cooled, then forced through cylindrical tubes (bags) where the dust collects on the inside walls. The bags are cleaned by either shaking or by the impingement of a blast of high pressure air. Collection efficiencies are extremely high, 99.9 percent or greater. Because of temperature limitations, fabric filters have not been accepted by the electric power industry to the extent that electrostatic precipitators have.

The final particulate collection device to be discussed is the electrostatic precipitator. In electrostatic separation, the flue gas is passed between two high voltage electrodes where the entrained gas particles become charged and are then drawn to and collected on the surface of the electrodes. The buildup of particles is continued until the efficiency of the unit falls to a predetermined level. The plates are then rapped and the particles fall to a collection hopper. Precipitators, the most common power plant particulate collection device, can be designed to operate at collection efficiencies as high as 99.9 percent.

In conclusion, control technology for the removal of particulates has been developed to the extent that it is possible to design and operate particulate collection devices at efficiencies sufficient to meet all Federal standards.

Comparison of Wood and Fossil-Fuel Emissions

In the previous sections boiler emissions and control technology for wood-fired and for fossil-fuel power plants were discussed. In this section a "fuel-source-to-bus-bar" summation is presented of atmospheric emissions for coal-, oil-, and wood-fueled systems taking into account the emission associated with the procurement, transportation, processing, and combustion of the fuel. The following 10 alternative fuel paths were analysed.

(1) Low-sulfur Western coal, surface mined, and train transported to Vermont

(2) High-sulfur (Pennsylvania bituminous) coal, deep mined, physically cleaned, and train transported to Vermont

(3) High-sulfur coal, deep mined, train transported to Vermont and combusted with stack gas cleanup

(4) High-sulfur coal, surface mined, physically cleaned, and train transported to Vermont

(5) High-sulfur coal, surface mined, train transported to Vermont, and combusted with stack gas cleanup

(6) Imported oil refined in the Caribbean, tanker transported to the east coast, and train transported to Vermont

(7) Domestic crude, pipeline transported from the southwest to a New Jersey refinery, refined and desulfurized, and train transported to Vermont

(8) Waste wood, harvested in Vermont, chipped, truck transported to the power plant, and combusted green

(9) Waste wood, harvested in Vermont, chipped, trucked to the power plant, dried and combusted

(10) Combined coal and wood wastes, green wood harvested, chipped, and truck transported. Coal deep mined, physically cleaned, and train transported.

Emission factors, in $lb/10^6$ Btu, are summarized in Table 14 for NO_x, SO_2, CO, particulates, and total organics for each of the 10 alternative fuel paths; rail and truck transport emission factors are expressed in terms of $lb/10^6$-ton-miles. Using the factors in Table 14 and the fuel requirements, process efficiencies, transport distances, etc., discussed in greater detail in the subsequent section on Energy Balances, total emissions for each path were calculated and summarized in Table 15. The basis for the calculations was the fuel requirement sufficient to supply a 50 MWe power plant.

It should be noted that more than half of the total emissions for wood-related systems shown in Table 15 is attributed to NO_x from the combustion step. The NO_x emission factor for wood combustion has not been determined accurately as yet. These values may be too high.

Study of the total emission ranking of the alternative fuel paths, displayed in Table 16, shows that the systems fall into three groups. The first group, including residual oil combustion and high-sulfur coal-fueled systems with stack gas cleanup, range in calculated emissions (total of NO_x, SO_2, CO, particulates, and total organics) from 2,135 to 2,625 tons/year. The second or intermediate emissions group including wood and high-sulfur, physically-cleaned coal systems have emissions that range from 3,675 to 4,095 tons/year. The wood-related systems would fall nearer the first group if the NO_x emissions during combustion are overstated in this calculation. The third, high emissions group, including low-sulfur Western coal and the combined wood- and coal-fired system have emissions of 5,150 and 5,465 tons/year, respectively. Because of the extremely high NO_x emission rates for wood-fired systems and the uncertainty in the NO_x emission factor, the emissions excluding NO_x were also included in Table 16. Comparing the 10 fuel supply paths under this basis shows that the paths now fall into a low and a high emission class. The low emission class now includes both green and dried wood along with oil and high-sulfur coal with stack gas scrubbing. From these comparisons it can be concluded that wood-fueled systems can compete favorably on an overall emissions (acceptability) basis with either coal- or oil-fired systems.

TABLE 14. SUMMARY OF "SOURCE-TO-POWER" UNIT AIR EMISSIONS FOR COAL, OIL, AND WOOD FUEL SYSTEMS

Fuel Supply Paths #	Energy System	Emissions lb/10^6 Btu Output					Reference No.
		NO_x	SO_2	CO	Particulates	Total Organics	
	Low Sulfur Western Coal						
1	Surface Mining	0.00008	Neg.[a]	Neg.	0.07	Neg.	14
	Rail Transport (lb/MM Ton-Mi)[b]	1848.5	131.8	1425.6	142.6	145.3	14
	Power Generation[c,d]	0.98	1.65	0.054	0.07	0.016	14
	Pennsylvania Bituminous Coal						
2	Deep Mining	0	0	0	Neg.	0	14
	Physical Cleaning	0.006	0.004	--[f]	0.01	—	14
	Rail Transport	1848.5	131.8	1425.6	142.6	145.3	14
	Power Generation[c,e]	0.68	1.443	0.038	0.044	0.011	14
3	Deep Mining	0	0	0	Neg.	0	14
	Rail Transport[b]	1848.5	131.8	1425.6	142.6	145.3	14
	Power Generation with Stack Gas Cleanup[c]	0.60	0.50	0.042	0.1	0.013	14
4	Surface Mining	0.0002	Neg.	Neg.	0.14	Neg.	14
	Physical Cleaning	0.006	0.004	--	0.01	--	14
	Rail Transport[b]	1848.5	131.8	1425.6	142.6	145.3	14
	Power Generation[c,e]	0.68	1.443	0.038	0.044	0.011	14
5	Surface Mining	0.0002	Neg.	Neg.	0.14	Neg.	14
	Rail Transport[b]	1848.5	131.8	1425.6	142.6	145.3	14
	Power Generation with Stack Gas Cleanup[c]	0.60	0.50	0.042	0.1	0.013	14
	Crude Oil						
6	Tanker Transport	0.0015	0.0016	0.0013	0.0021	$9x10^{-5}$	14
	Rail Transport[b]	1848.5	131.8	1425.6	142.6	145.3	14
	Power Generation[c,g]	0.70	0.529	0	0.05	0.01	14
7	Domestic Oil Pipeline	0.009	0.016	$2x10^{-5}$	0.002	0.0003	14
	New Jersey Refined with Desulfurization	0.023	0.12	0.003	0.002	0.025	14
	Rail Transport[b]	1848.5	131.8	1425.6	142.6	145.3	14
	Power Generation[c,g]	0.70	0.529	0	0.05	0.01	14

TABLE 14. (Continued)

Fuel Supply Paths #	Energy System	Emissions lb/10^6 Btu Output					Reference No.
		NO$_x$	SO$_2$	CO	Particulates	Total Organics	
	Waste Wood						
8	Wood Recovery	0.05	0.004	0.030	0.002	0.005	2
	Process Chipping	0.118	0.009	0.072	0.004	0.012	2
	Truck Transport(b)	4595.0	364.5	3037.5	175.5	499.5	2
	Power Generation (Green Chips)(c,h)	1.235(l)	0.074(i)	0.247	0.210	0.247	2
9	Wood Recovery	0.05	0.004	0.030	0.002	0.005	2
	Process Chipping	0.118	0.009	0.072	0.004	0.012	2
	Truck Transport(b)	4995.0	364.5	3037.5	175.5	499.5	2
	Chip Drying	Neg.	Neg.	Neg.	Neg.	Neg.	
	Power Generation (Dried Chips)(c,j)	1.235(l)	0.074	0.247	0.210	0.247	2
10	Wood Recovery	0.05	0.004	0.030	0.002	0.005	2
	Process Chipping	0.118	0.009	0.072	0.004	0.012	2
	Truck Transport(b)	4995.0	364.5	3037.5	175.5	499.5	2
	Deep Mine (Coal)(k)	0	0	0	Neg.	0	14
	Rail Transport(b)	1848.5(l)	131.8	1425.6	142.6	145.3	14
	Power Generation with Green Wood and Coal(c)	1.090	0.480	0.186	0.177	0.177	2,14

(a) Neg. - Negligible.

(b) Emission factor expressed in lb/10^6 ton-mile.

(c) Emissions based on 1 x 10^6 Btu input.

(d) Base on 0.8 percent sulfur coal.

(e) Emission factor for physical cleaning with environmental controls, 1 percent sulfur coal after cleaning.

(f) --: Insufficient information to assign emission factor number, however, emission will be low.

(g) 0.5 percent sulfur residual oil.

(h) Based on heating value of 4050 Btu/lb.

(i) Based on 80 percent wood, 20 percent bark.

(j) Emissions assumed the same as green chip combustion.

(k) Physically cleaned coal.

(l) Factor not accurately determined, may be too high.

TABLE 15. SUMMARY OF "SOURCE-TO-POWER" AIR EMISSIONS FOR COAL, OIL, AND WOOD FUEL SYSTEMS

Fuel Supply Paths #	Energy System	Emissions Ton/Year (Basis 50 MWe Plant)(a)					Grand Total
		NO_x	SO_2	CO	Particulates	Total Organics	
	Low Sulfur Western Coal						
1	Surface Mining	0.1	-	-	113.1	-	
	Rail Transport(b)	282.8	20.2	218.1	21.8	22.2	
	Power Generation	1582.7	2664.8	87.2	113.1	25.8	
	Total(c)	1865.6	2685.0	305.3	248.0	48.0	5151.9
	Pennsylvania Bituminous Coal						
2	Deep Mining(d)	0	0	0	-	0	
	Physical Cleaning(d)	15.9	10.6	-	26.5	-	
	Rail Transport(e)	45.5	3.2	35.1	3.5	3.6	
	Power Generation	1098.2	2330.4	61.4	71.1	17.8	
	Total(f)	1159.6	2344.2	96.5	101.1	21.4	3722.8
3	Deep Mining(g)	0	0	0	-	0	
	Rail Transport(e)	49.1	3.5	37.8	3.8	3.9	
	Power Generation with Stack Gas Cleanup	1144.1	870.1	73.1	174.0	22.6	
	Total(g)	1193.2	873.6	110.9	177.8	26.5	2382.0
4	Surface Mining(d)	0.5	-	-	371.2	-	
	Physical Cleaning(d)	15.9	10.6	-	26.5	-	
	Rail Transport(e)	45.5	3.2	35.1	3.5	3.6	
	Power Generation	1098.2	2330.4	61.4	71.1	17.8	
	Total(f)	1160.1	2344.2	96.5	472.3	21.4	4094.5
5	Surface Mining(g)	0.3	-	-	243.6	-	
	Rail Transport(e)	49.1	3.5	37.8	3.8	3.9	
	Power Generation with Stack Gas Cleanup	1144.1	870.1	73.1	174.0	22.6	
	Total(g)	1193.5	873.6	110.9	421.4	26.5	2625.9
	Crude Oil						
6	Caribbean Refined	0(h)	0	0	0	0	
	Tanker Transport	2.4	2.6	2.1	3.4	0.1	
	Rail Transport(i)	21.1	1.5	16.3	1.6	1.7	
	Power Generation	1130.5	854.3	-	80.8	16.2	
	Total(j)	1154.0	858.4	18.4	85.8	18.0	2134.6

TABLE 15. (Continued)

Fuel Supply Paths #	Energy System	Emissions Ton/Year (Basis 50 MWe Plant)(a) NO_x	SO_2	CO	Partic- ulates	Total Organics	Grand Total
7	Domestic Oil Pipeline	14.5	25.8	0.0	3.2	0.5	
	New Jersey Refined with Desulfurization	37.1	193.8	4.8	3.2	40.4	
	Rail Transport(i)	21.1	1.5	16.3	1.6	1.7	
	Power Generation	1130.5	854.3	-	80.8	16.2	
	Total(j)	1203.2	1075.4	21.1	88.8	58.8	2447.3
	Waste Wood						
8	Wood Recovery(k)	80.8	6.5	48.5	3.2	8.1	
	Process Chipping(k)	190.6	14.5	116.3	6.5	19.4	
	Truck Transport(l)	59.9	4.4	36.5	2.1	6.0	
	Power Generation	1994.5(q)	119.5	398.9	339.2	398.9	
	Total(k)	2325.8	114.9	600.2	351.0	432.4	3824.3
9	Wood Recovery(m)	56.7	4.5	34.0	2.3	5.7	
	Process Chipping(m)	133.8	10.2	81.6	4.5	13.6	
	Truck Transport(l)	42.0	3.1	25.5	1.5	4.2	
	Chip Drying	0.0	0.0	0.0	0.0	0.0	
	Power Generation	1994.5(q)	119.5	398.9	339.2	398.9	
	Total(n)	2227.0	137.3	540.0	347.5	422.4	3674.2
10	Wood Recovery(o)	561.	4.5	33.7	2.2	5.6	
	Process Chipping(o)	132.4	10.1	80.8	4.5	13.5	
	Truck Transport(l)	41.5	3.0	25.2	1.5	4.2	
	Deep Mine (Coal)(p)	0	0	0	Neg.	0	
	Rail Transport(e)	13.8	1.0	10.6	1.1	1.1	
	Power Generation with Green Wood and Coal	1760.4(q)	773.0	300.4	285.9	285.9	
	Total(o,p)	2004.2	791.6	450.7	295.2	310.3	3852.0

(a) Emissions calculated based on emission factors presented in Table 14, and energy production of 3.22×10^{12} Btu
(b) Transport distance - 1800 miles
(c) Basis: 170,000 ton coal/yr., 9500 Btu/lb.
(d) Quantity handled - 202,400 tons/yr.
(e) Transport distance - 400 miles
(f) Basis: 123,000 ton coal/yr., 13100 Btu/lb.
(g) Quantity handled - 132,840 ton coal/yr., 13100 Btu/lb.
(h) Emissions considered zero because refining done outside United States
(i) Transport distance - 300 miles
(j) Basis - 511,760 Bbl. (76,000 tons), 6.29×10^6 Btu/Bbl.
(k) Basis - 410,000 ton green wood/yr., 4050 Btu/lb.
(l) Transport distance - 60 miles
(m) Quantity handled - 280,000 ton green wood/yr. 4050 Btu/lb.
(n) Dried Wood Chips - 5800 Btu/lb.
(o) Quantity handled - 277,079 ton green wood/yr. 4050 Btu/lb.
(p) Quantity handled - 37,214 ton coal/yr., 13100 Btu/lb.
(q) Overestimated if emission factor is too high.

TABLE 16. AIR POLLUTION RANKING OF ALTERNATIVE FUEL PATHS

Fuel Path Description	Total Emissions,[(a)] tons/yr	Rank	Emissions Excluding NO_x, tons/yr	Rank
Imported residual oil	2135	1	980	1
High sulfur coal, deep mined, stack gas clean up	2380	2	1190	2
Domestic refined oil	2450	3	1245	3
High sulfur coal, surfaced mined, stack gas clean up	2625	4	1430	4
Waste wood, dried	3675[(b)]	5	1445	5
High sulfur coal, deep mined, physically cleaned	3725	6	2565	8
Waste wood, green	3825[(b)]	7	1500	6
Waste wood and physically cleaned coal	3852[(b)]	8	1848	7
High sulfur coal, surfaced mined, physically physically cleaned	4095	9	2935	9
Low sulfur western coal	5150	10	3285	10

(a) Includes NO_x, SO_2, CO, particulates, and total organics.

(b) Overestimated if NO_x emission factor from combustion is too high.

Summary

The following paragraphs summarize the previous discussions relating to pollutant emissions and control technology for wood-fueled power generation.

Air Pollution Emissions

Wood-fueled systems ranked fifth and seventh in total emissions of the ten coal-, oil-, and wood-fuel paths considered. Partially dried wood and green wood has the following calculated annual emissions for a 50 MWe power plant.

	Emissions, ton/yr					
	NO_x	SO_2	CO	Particulate	Total Organics	Total
Dried Wood (280,000 ton wood/yr)	2,227	136	540	348	423	3,675
Green Wood (410,000 ton wood/yr)	2,326	115	600	351	432	3,825

Wood-fueled systems had lower emissions than high sulfur, physically cleaned coals (3,725-4,095 ton/yr), low-sulfur Western coal (5,150 ton/yr), and combined wood and coal-fueled systems (3,852 ton/yr). Residual oil (2,135-2,450 ton/yr) and coal-fueled systems with stack gas cleanup (2,380-2,625 ton/yr) had lower total emissions.

Emission rates for all pollutants appear to be low enough, or controllable to meet all existing State or Federal air pollution regulations. However, the estimated NO_x emission rate of 1.235 $lb/10^6$ Btu is significantly higher than the 0.7 $lb/10^6$ Btu Federal new source performance standards for coal-fired power plants. While not in violation of new source standards, which apply only to fossil-fuel power generation, the estimated NO_x emission rate is high enough for concern. Study of the data used to calculate the NO_x emission rate shows that it was not obtained from actual testing, but from estimates from similar combustion sources.(9) The accuracy of this factor is, therefore, uncertain at this time. In addition, the emission rate (originally expressed as lb/ton) was converted to lb/10^6 Btu employing an average heating value of 4200 Btu/lb. Use of a significantly higher value would reduce the calculated NO_x emission rate. Therefore, the significance of the difference between the calculated rate and the standard is questionable. In any event, modification of the boiler design to restrict excess air could be employed to reduce NO_x emissions.

The control of particulate emissions from wood-fueled power generation can be accomplished by a number of control systems. Noted below is a brief summary of the control method effectiveness and rough estimates of collector costs excluding fans, ducting, etc., for a 50-MWe wood-fueled power plant.

	Collection Efficiency, percent	Installed Cost, $1000	Annualized Cost, $1000
Cyclone-scrubber	99.9	422-633	192-264
Wet scrubber	99.8	480-752	800-1040
Electrostatic precipitator	98.7	672-848	112-144
Fabric filter	99.9	752-1040	240-288

As can be seen, the cyclone-scrubber system and the electrostatic precipitator collector have the lowest annualized control costs. Of the two, the multitubular cyclone in series with a low-energy scrubber system is the overwhelming favorite. (There is no proven performance of electrostatic precipitators on waste wood boilers.) This choice is based on the cyclone-scrubber system's relative low capital cost, reasonable operating expenses, sufficiently high collection efficiency, ease of maintenance, proven performance, and low generation of concentrated (easily disposed) scrubber sludge.

During periods of incomplete combustion, organic chemicals (primarily hydrocarbons) which are normally oxidized to CO_2 and water are released to the atmosphere. There is a potential that these chemicals could react with each other to form either carcinogenic or photochemically active hazardous compounds. Investigation shows that while some small fraction of these chemicals could be emitted, there is no evidence that their emission will be significant to the local air quality or present local health problems. Emissions of these materials, for example, are estimated to be less with wood firing than for a correspondingly sized coal-fired power plant.

Boiler Residue

Although available information on boiler residue disposal is limited, disposal of the boiler ash, clinker, and fly ash is not considered to present a problem. The boiler residue is composed primarily of inert alumina and silica with trace (part per billion) amounts of heavy metals. Disposal of this material in an environmentally acceptable manner is accomplished through disposal in landfills or, when collected in slurry form, in lined lagoons.

Information on by-product uses is tentative. Attempts have been made to employ the boiler residue as a soil conditioner; however, at this time, no information is available regarding the success or failure of these attempts.

Conclusions

These conclusions are summarized below:

- **The use of waste wood to fuel boilers for the generation of electricity is environmentally acceptable method of power generation.**
- **Total air emissions for 100 percent wood-fueled systems are comparable or less than alternative fuels such as physically cleaned coal or low-sulfur Western coals. The waste wood and coal combination has comparable total air emissions.**
- **Control technology for the collection of up to 99.9 percent of the particulates is currently available. The most promising control method**

identified is a multitubular cyclone separator connected in series with a low-energy wet-impingement scrubber. This system has proven economical, dependable, and effective in actual waste wood boiler application.

- Emission of hazardous organic chemicals from the incomplete combustion of wood should not present any significant problems to the local air quality.
- Environmentally acceptable disposal of boiler residues can be accomplished by placing the relatively inert boiler ash and fly ash in landfills or in lined lagoons.

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ENERGY BALANCE ANALYSIS

Introduction

In considering the economic and technical feasibility of firing an electric utility boiler with wood wastes in Central Vermont, it is appropriate to consider the overall energy use associated with wood fuel as compared with that for alternate fueling options. This section sets out the energy consumed in the recovery, processing, and transport of fuel to Central Vermont by the ten alternative fuel paths described in the preceding analysis of overall atmospheric emissions.

Figure 30 is an illustration of the fueling paths which were analyzed for their energy consumptions. Path 10 is not illustrated but is a combination of Paths 1 (except Pennsylvania coal is substituted for Wyoming coal) and 8. The estimated energy requirements, associated with the conventional-fuel paths are compared with energy estimates for recovering, processing, and transporting wood chips in the Central Vermont area.

Data for energy consumed in the various fuel recovery, preparation, and transportation paths are presented first to establish the basis and sources of the information. This is followed by an analysis of the energy consumption for the 10 fueling paths to supply a 50 MWe plant in Central Vermont. In conclusion, summary data are presented for all fuel paths investigated.

Basic Data and Sources of Information

Pennsylvania Bituminous Coal

A review of available Pennsylvania coal that may be physically cleaned to produce a total sulfur content below 1 percent indicates that only a few coalbeds in specific counties can qualify.(1)* These counties

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*References for this section are listed on Page 124

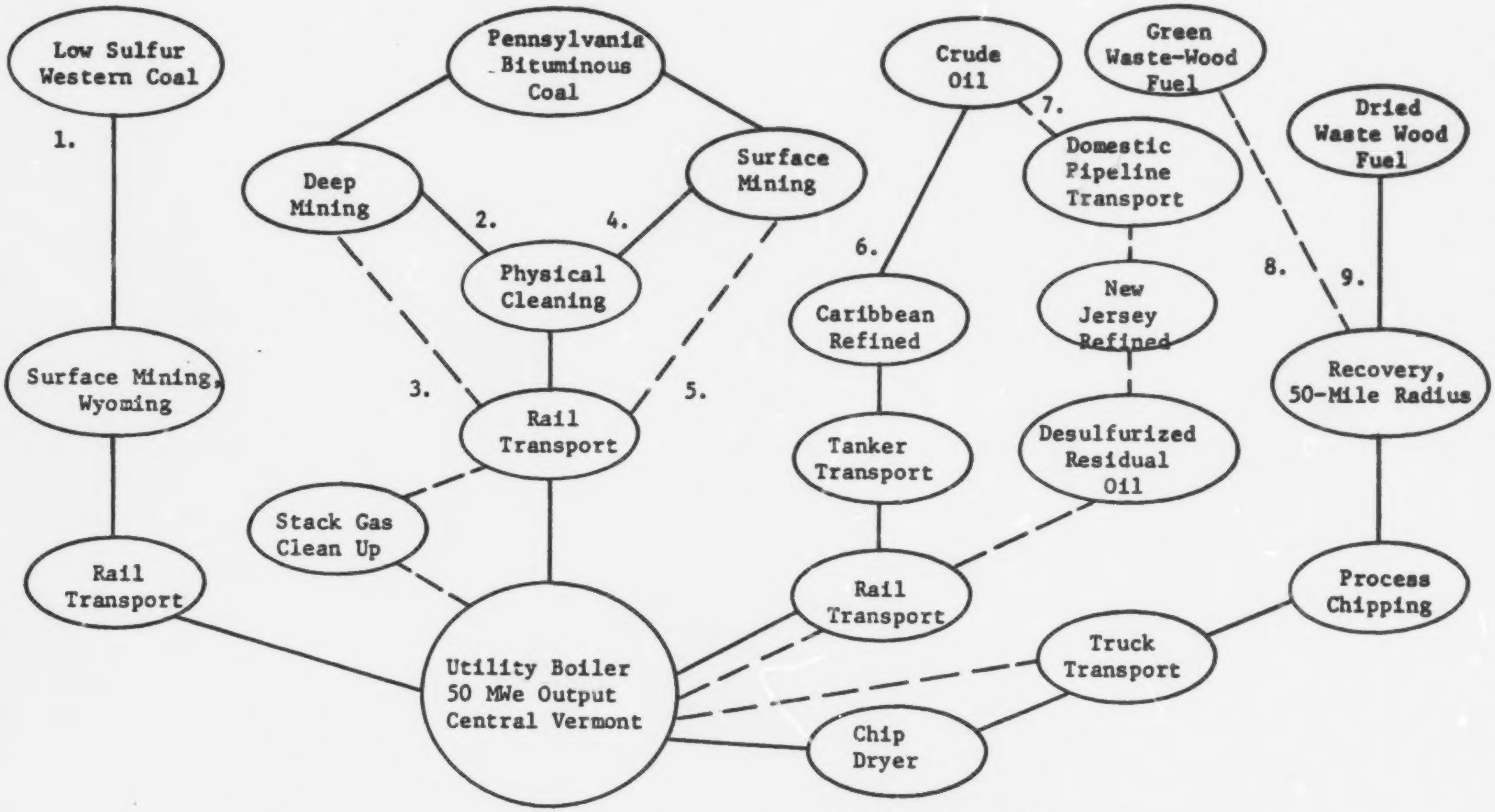
Low Sulfur Western Coal
1.
Surface Mining, Wyoming
Rail Transport
Pennsylvania Bituminous Coal
Deep Mining
Surface Mining
2.
4.
Physical Cleaning
3.
5.
Rail Transport
Stack Gas Clean Up
Utility Boiler 50 MWe Output Central Vermont
Crude Oil
7.
6.
Domestic Pipeline Transport
Caribbean Refined
New Jersey Refined
Tanker Transport
Desulfurized Residual Oil
Rail Transport
Green Waste-Wood Fuel
Dried Waste Wood Fuel
8.
9.
Recovery, 50-Mile Radius
Process Chipping
Truck Transport
Chip Dryer

FIGURE 30. FUEL PATHS FOR PUBLIC UTILITY ELECTRIC POWER IN CENTRAL VERMONT

Fuel Path Identification

1. Western (Wyoming) Coal
2. Penn. Bit. - Deep Mined - Physically Cleaned
3. Penn. Bit. - Deep Mined - Stack Gas Cleaned
4. Penn. Bit. - Surface Mined - Physically Cleaned
5. Penn. Bit. - Surface Mined - Stack Gas Cleaned
6. Caribbean Residual Fuel
7. Domestic Crude - Pipeline-Refined-Desulfurized
8. Green Wood Chips
9. Dried Wood Chips
10. Combined Coal/Green Wood Chips

were identified and selected for energy balance analysis. Both surface and deep mining operations were analyzed for the selected coalbeds.

Recovery - Deep Mining. Cost analysis of underground Eastern coal mining has been reported.(2) A mining capacity of 1.06 million tons per year was selected as being representative of the Pennsylvania coalbed operations. The total electric power for an operation of this size is 21.5×10^6 kwh per year and is equivalent to 69,000 Btu per ton of coal. Fuels and lubricant consumptions represent an additional 81,000 Btu per ton of coal.*

Recovery - Surface Mining. Data for energy consumption for surface mining for Pennsylvania were not located. Analyses of costs made in 1972(3) for contour surface mining in Northern West Virginia for a 1-million ton per year capacity were considered acceptable for the purpose at hand. A separate analysis was made in 1974(4) and it was also used for comparison purposes.

In the Northern West Virginia operation(3), the electrical consumption amounts to 92,200 Btu per ton of raw coal. Fuels and lubricants account for another 111,000 Btu per ton. The data for the Eastern Province in Reference 4 is for a mining operation of 4.8 million tons per year. The electric power consumption amounts to 45,600 Btu per ton of raw coal; fuel and lubricants account for 34,400 Btu per ton. A 3-million-ton-per-year Northern West Virginia mine was also examined.(3) The electric power value is 124,000 Btu/ton and fuel use is 60,000 Btu/ton. Inquiries concerning these data indicate that the data of Reference 3 are more appropriate for the present study.

Recovery - Wyoming Surface Mining. Reference 3 contains information on the costs of power and fuel for a 5-million-ton-per-year low-sulfur coal surface mine. The electric power consumption is calculated to be only

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*The national average price of distillate fuel was taken as $2.61 per million Btu.

7060 Btu per ton of raw coal while the fuels, lubricants and so forth account for 25,000 Btu per ton.

Data for a dozen Wyoming County coalbeds were examined(5) and the average mositure content was found to be about 16.5 percent. An average heating value of 19 x 10^6 Btu per ton is considered appropriate.

Physical Cleaning of Pennsylvania Bituminous Coal

In the Northern Appalachian Region, the sulfur content of bituminous coal averages about 3.07 percent total with the pyritic sulfur representing 2.03 percent. Consequently, it is essentially impossible to physically clean the average coal to less than 1 percent. Some exceptions in the Pennsylvania region are the Upper and Lower Freeport and Kittanning beds in certain counties in which the average sulfur content is about 1.7 percent. The losses of raw coal incurred in cleaning such coals to a sulfur content of 1 percent or less might not exceed 10 percent of the total raw coal energy content, i.e., 90 percent energy recovery.*

The energy consumed by dewatering centrifuges, crushers, screen vibrators and the like amount to about 24,000 Btu per ton of product.(6,7) The energy for drying the coal consumes about 25 pounds of cleaned product per ton of product. This will require about 28 pounds of raw coal or about 360,000 Btu per ton of product.

The remaining energy consumption is for the disposal/reclamation of the refuse from the cleaned coal--pyritic sulfur plus tailings. It is understood that this material could easily catch fire through spontaneous combustion unless properly disposed. Alternate layers of refuse and impervious clay have been utilized effectively and is probably entirely appropriate for physical cleaning operations. It is estimated that 20 tons of refuse disposed in this fashion would require a total of 380,000 Btu. This includes loading, bulldozing refuse, shoveling clay and bulldozing clay. (It does not include mulching, liming, fertilizing, and seeding as this is a surface mining reclamation operation.) This results in a consumption of about 6,000 Btu per ton of product, a relatively small portion of the total.

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* Cleaning of other Northern Appalachian coals to less than 1 percent sulfur would entail total Btu losses of 20-30 percent or more.

Stack Gas Scrubbing

Wet scrubbing stack gas cleanup systems have primary energy consumption in the fans and pumps and these can amount to about 6 percent of the plant operating capacity.(8) Another source(9) presented information on selected systems and concluded that the sodium scrubber energy consumption could account for 35 percent of operating cost; this could be reduced to 12 percent by using a double effect evaporator-crystallizer.

An overall value for energy consumption of about 6 to 11 percent of plant operating capacity appears to encompass the probable range.

Low Sulfur Oil

Recovery. The energy for recovering crude oil is considered to be negligible in comparison with the refining and desulurization processing.

Refining. Data developed by the Bureau of Mines indicate that the average for all U.S. in 1973 was 674,000 Btu per barrel of crude.(10)

Desulfurization. Detailed data for desulfurizing oil were not located. However, it is the consensus of experienced personnel that the energy for desulfurizing residual fuel will run about 75 percent of that for refining. This places the consumption at about 500,000 Btu per barrel of fuel.

Transportation, Truck, Rail, and Pipeline

A study was conducted recently at Battelle(11) to determine the transport energy consumptions for both truck and rail. The energy consumption for trucks was calculated, using national data, to be 1730 Btu per net ton-mile. Rail consumption was similarly established as 680 Btu per net ton-mile. An independent reference(12) places these two values at 2400 and 670 Btu per net ton-mile, respectively.

Field data were used to determine the energy consumption for pumping crude oil in a transcontinental pipeline. The operation was assumed to be a 40-inch pipeline transporting 750,000 barrels of crude per day. The crude had a viscosity of 100 SSU and a specific gravity of 0.85. Field data analysis(13) indicate that the energy consumption is 93 Btu per ton-mile. This value is considered accurate to within 20 percent.

Green Wood Chip

Data on the energy consumption for the recovery and preparation of green wood chips for boiler fuel were not readily available. Generally, the literature which was reviewed contained information for smaller operations performed on a laboratory basis and it was not considered to be necessarily appropriate for theanalysis of interest here. Therefore, data were sought from a variety of sources, all of which were actively engaged in forestry management and commercial utilization of wood wastes as fuels. These findings are summarized in the following paragraphs.

Recovery and Preparation. No specific information could be obtained for the exact quantities of energy consumed in the recovery of forest wood wastes. However, one source had what is believed to be very good data for both recovery of wastes and their preparation and chipping.(14) During 1974, one diesel-powered disk-type Morbark chip harvester produced 52,000 tons of wood chips and complete cost records for fuel and energy consumption were maintained. The operation included recovery, preparation, chipping, and the blowing of the chips into a truck van. The mobile chipper operated in good forestry conditions and forest wastes were transported a distance of the order of 1/4 mile to the chipper. The operations, though not exactingly separable in terms of energy consumption, could be rather well estimated. Accordingly, it was estimated that 70 percent of the total energy consumed was for wood preparation and chipping while the balance was for recovery. This permits a breakdown of the energy consumed per ton of green chips as follows:

• recovery	140,000 Btu/ton
• preparation and chipping	330,000 Btu/ton

Another source of information had data for an operation producing wood chips for pulp and paper production.(15) Some 12 sets of production figures and power consumptions were obtained. It was estimated by the source that 15 percent of the total was for recovery. The range was as presented below for recovery and preparation and chipping.

	production, tons	Btu per ton
• recovery		
maximum	42,970	8,585
minimum	11,056	18,522
typical	38,245	9,686
• chipping		
maximum	42,970	48,650
minimum	11,056	104,958
typical	38,245	54,888

Another source(16) had collected much information from their member pulpwood companies and this was being analyzed so that energy consumption values could be established. They found that their data were often incomplete but it broke down into 11 different kinds of logging operations representing pulpwood production regions. The range of energy consumed is as follows:

• recovery	30,000 to 180,000 Btu per ton of chips
• chipping and trucking	300,000 Btu per ton of chips

The source advises that he distrusts the data at this stage of analysis. Nonetheless, it appears to be of the right order.

Of these operations described, it is believed that the Total Chips Incorporated operation(14) is more closely related to the kind that is proposed for the Central Vermont region. Good forestry practice was utilized and wood types were somewhat similar to those in Vermont. For these reasons, the energy consumption data provided by Total Chips Incorporated have been selected for energy balance analysis.

Transportation. The previously cited information was utilized and the value of 1730 Btu per ton-mile was used. It was established that the operation would be within 60 miles on the electric utility plant and an average trip would be 40 miles one way or a weighted value of 60 miles per round trip (40 miles empty).

Quantity of Green Chips Required. The quantity will be dependent upon the heating content per unit of weight and this, in turn, is dependent upon moisture content. The basis of 9.35×10^6 Btu per ton (45 percent moisture) was used.

For a heating value of 9.35×10^6 Btu per ton, about 410,000 tons of green wood chips will be required annually for the 50 MWe plant with the assumed load factor of 70 percent, and a power plant efficiency of 27.4 percent.

Annual Energy Consumption for Selected Paths

For purposes of comparison, the 10 fueling options were analyzed, using the foregoing data, to determine the annual energy consumed in the recovery, preparation, and transport of the fuel to Central Vermont in the quantities required for a 50 MWe plant. The data for each are set forth in a series of tables.

The quantity of each fuel required annually depends upon the heating value of the fuel and the power plant efficiency for that fuel. For the fossil fuels, an overall power plant efficiency of 32.5 percent, equivalent to a heat rate of 10,500 Btu/kwhr, was assumed. For a 50 MWe plant operating at 70 percent load factor, the annual heat input requirement would be 3.22×10^{12} Btu. For green wood, the overall power plant efficiency was assumed to be 27.4 percent, or about 12,450 Btu/kwhr. The annual heat input requirement in this case would be about 3.80×10^{12} Btu/year.

(1) Wyoming Low Sulfur Coal. The information on energy consumption is presented in Table 17. As the sulfur content is below 1 percent no energy is consumed in coal cleaning or stack gas cleanup.

(2) Pennsylvania Bituminous Coal, Deep Mined, and Physically Cleaned. The detailed energy consumptions associated with the use of physically cleaned high-sulfur coal are presented in Table 18. In the cleaning of this coal the Btu content of the cleaned product and refuse were treated as equal in this analysis. Actually, the product would be expected to increase in heat content while the refuse would be consequently lowered. When all refuse coal, dewatering and drying are taken into account, nearly 13 percent of the raw mined high-sulfur coal is consumed in preparation of clean coal.

(3) Pennsylvania Bituminous Coal, Deep Mined, and Stack Gas Cleaned. As may be seen in Table 19, the energy consumption for stack gas cleaning is significantly lower than for physically cleaned coal.

(4) Pennsylvania Bituminous Coal, Surface Mined, and Physically Cleaned. The energy consumption for mining is overwhelmed by the physical cleaning processing energy requirements. These details are shown in Table 20.

(5) Pennsylvania Bituminous Coal, Surface Mined, and Stack Gas Cleaned. This fueling path is presented in Table 21. The energy consumed in stack gas cleaning is significantly lower than for physically cleaned coal.

(6) Caribbean Residual Fuel. The residual fuel is recovered, processed, and transported by tanker to a nearby seaport. Hence, no domestic energy is consumed by this fueling option other than for rail transport of the fuel oil, Table 22.

(7) Domestic Crude Oil. This alternative path for obtaining low-sulfur residual fuel was examined in the event a foreign curtailment might prevent the procurement of the needed fuel. For this case, crude was pipelined from the South-Central region of the U.S. to a New Jersey refinery where it was processed into low-sulfur residual fuel. As may be seen from Table 23, the energy consumed in preparation or processing overwhelms the transportation energy consumption.

TABLE 17. ENERGY CONSUMPTION FOR PATH 1, WYOMING LOW-SULFUR COAL

Heating Value: 19×10^6 Btu/ton
Quantity Required: 170,000 tons/year to provide 3.22×10^{12} Btu

Activity			Annual Energy Consumption, 10^6 Btu
Recovery			
Surface Mining, Electric Power - 25,000 Btu/ton	4,250		
Fuel and Lubricants - 7,100 Btu/ton	1,207		
			5,457
Preparation			None
Transportation			
Rail - 170,000 tons, 1800 miles at 680 Btu/ton-mile			208,080
		Total	213,573

TABLE 18. ENERGY CONSUMPTION FOR PATH 2, PENNSYLVANIA BITUMINOUS COAL - DEEP MINED AND PHYSICALLY CLEANED

Heating Value: 26.2×10^6 Btu/ton
Quantity Required: 123,000 tons/year of cleaned coal to provide 3.22×10^{12} Btu

Activity			Annual Energy Consumption, 10^6 Btu
Recovery			
Deep mined, Mined Coal - 136,700 tons			
Electric Power - 69,000 Btu/ton	9,432		
Fuel and Lubricants - 81,000 Btu/ton	11,072		
			20,505
Preparation			
Physical Cleaning (90% average **Btu yield**)			
Coal rejected - 13,670 tons @ 26.2×10^6 Btu/ton		358,100	
Electric Power (24,000 Btu/ton)		2,952	
Drying Using cleaned coal, 25 lbs/ton or 28 lbs raw coal/ton = 360,000 Btu/ton		44,280	
Rejected coal disposal - 6000 Btu/ton of product		738	
			406,070
Transportation			
Rail - 123,000 ton, 400 miles @ 680 Btu/ton-mile			33,456
		Total	460,030

TABLE 19. ENERGY CONSUMPTION FOR PATH 3, PENNSYLVANIA BITUMINOUS COAL, DEEP MINED, BURNED WITH STACK GAS CLEANING

Heating Value: 26.2×10^6 Btu/ton
Quantity Required: 133,700 tons/year to provide 3.22×10^{12} Btu net input to power plant.

Activity		Annual Energy Consumption, 10^6 Btu
Recovery		
Deep Mined (mined coal 133,700 tons)		
Electric, 69,000 Btu/ton	9,225	
Fuel and Lubricants, 81,000 Btu/ton	10,830	
		20,055
Preparation		
Stack Gas Cleaning 8% of input Btu's		280,000
Transportation		
Rail - 133,700 tons, 400 miles @ 680 Btu/ton-mile		36,366
	Total	336,421

TABLE 20. ENERGY CONSUMPTION FOR PATH 4, PENNSYLVANIA BITUMINOUS COAL, SURFACE MINED AND PHYSICALLY CLEANED

Heating Value: 26.2×10^6 Btu/ton
Quantity Required: 123,000 tons/year of cleaned coal to provide 3.22×10^{12} Btu

Activity		Annual Energy Consumption, 10^6 Btu
Recovery		
Surface Mined - mined coal 136,700 tons		
Electric Power - 92,200 Btu/ton	12,603	
Fuel and Lubricants - 111,000 Btu/ton	15,173	
		27,777
Preparation		
Physical Cleaning - 90% average yield		
Coal Rejected - 13,670 tons @ 26.2×10^6 Btu/ton	358,100	
Electric Power - 24,000 Btu/ton	2,952	
Drying using cleaned coal, 25 lbs per ton or 28 lbs of raw coal/ton = 360,000 Btu/ton	44,280	
Rejected coal disposal - 6000 Btu/ton of product	738	
		406,070
Transportation		
Rail - 123,000 ton, 400 miles @ 680 Btu/ton-mile		33,456
	Total	467,300

TABLE 21. ENERGY CONSUMPTION FOR PATH 5, PENNSYLVANIA BITUMINOUS COAL, SURFACE MINED, BURNED WITH STACK GAS CLEANING

Heating Value: 26.2 x 10^6 Btu/ton
Quantity Required: 133,700 tons/year to provide 3.22 x 10^{12} Btu net input to power plant.

Activity		Annual Energy Consumption, 10^6 Btu
Recovery		
Surface Mined - mined coal - 133,700 tons		
Electric Power - 92,200 Btu/ton	12,327	
Fuel and Lubricants - 111,000 Btu/ton	14,840	
		27,167
Preparation		
Stack Gas Clean-up 8% of input Btu's		280,000
Transportation		
Rail - 133,700 tons, 400 miles @ 680 Btu/ton-mile		36,366
Total		343,533

TABLE 22. ENERGY CONSUMPTION FOR PATH 6, CARIBBEAN RESIDUAL FUEL - TANKER TO NEW YORK/BOSTON

Heating Value: 6.29×10^6 Btu/bbl
Quantity Required: 511,760 bbl/year residual fuel oil to provide 3.22×10^{12} Btu

Activity		Annual Energy Consumption, 10^6 Btu
Recovery		None Domestically
Preparation		None Domestically
Transportation		
Rail - 76,000 tons, 300 miles @ 680 Btu/ton-mile		15,500
	Total	15,500

TABLE 23. ENERGY CONSUMPTION FOR PATH 7, DOMESTIC CRUDE OIL - REFINED AND DESULFURIZED

Heating Value: 6.29×10^6 Btu/bbl
Quantity Required: 511,760 bbl/year residual fuel oil to provide 3.22×10^{12} Btu

Activity		Annual Energy Consumption, 10^6 Btu
Recovery (from well)		Negligible
Transportation (to refinery in New Jersey)		
Pipeline - 76,000 tons, 1400 miles @ 93.1 Btu/ton-mile		9,906
Preparation		
Refining (674,000 Btu/bbl)	344,926	
Desulfurization (500,000 Btu/bbl)	255,880	
		600,806
Transportation		
Rail - 76,000 tons, 300 miles @ 680 Btu/ton-mile		15,504
Total		626,216

(8) Green Wood Waste Chips. The energy consumed for the green wood chip fueling of a boiler in Central Vermont is presented in Table 24. The total annual energy consumption is estimated at 235,000 x 10^6 Btu for recovery, chipping, and transportation. An independent, and preliminary, analysis indicates that the annual consumption would be 168,300 x 10^6 Btu.(17)

(9) Dried Wood Wastes (15 percent moisture). A review(18) of a paper company's operation of a newly designed wood-fired boiler revealed that it should be possible to utilize stack gas heat to dry wood chips as they are fed to the fuel feeding system of the boiler. Generally, the moisture content of the wood wastes may run about 45 percent and this will provide an overall steam-boiler conversion efficiency of about 68 percent. A dryer could be installed using 750F stack gases to dry the wood chips to a moisture content of about 15 percent. The heating value of the dried chips would be raised to about 14.5 x 10^6 Btu/ton. In addition, the steam-raising efficiency would increase to about 77 percent and the overall power plant efficiency would increase to about 30.8 percent. The annual wood requirement would be reduced more than 11 percent to 363,000 tons of green wood (45 percent M.C.) which is equivalent to 235,000 tons of dried wood (15 percent M.C.). As shown in Table 25 this will reduce the energy consumption by the same percentage, to 208,000 x 10^6 Btu when compared with green wood chip utilization.

(10) Combined Coal/Green Waste Wood. It was believed that a fuel path in which both coal and wood chips were simultaneously fired beneath a boiler at a ratio such as to provide not more than 1 percent total sulfur content, would have a low recovery-to-boiler energy consumption. The Pennsylvania coalbeds contain an average of 3.3 percent total sulfur. Thus, to provide a 1 percent maximum of sulfur, the coal must be 0.303 times the total heat input to the power plant. The balance must be wood. The steam raising efficiency, estimated on a proportional basis, would be about 72.5 percent, giving an overall power plant efficiency of 29 percent. The heat input requirement thus becomes 3.60 x 10^{12} Btu/year. A fuel mixture of 1.09 x 10^{12} Btu or 41,633 tons of coal per year plus 2.51 x 10^{12} Btu or 268,363 tons of green wood chips per year would provide the equivalent of a 1 percent sulfur fuel. As will be seen in Table 26, the annual energy consumed by these combined paths is 173,771 x 10^6 Btu.

TABLE 24. ENERGY CONSUMPTION FOR PATH 8, GREEN WASTE WOOD - CHIP AND TRUCK

Heating Value: 9.35×10^6 Btu/ton (45% M.C. wet, 8500 Btu/dry lb)
Quantity Required: 410,000 tons/year (Plant efficiency = 27.6 percent)

Activity		Annual Energy Consumption, 10^6 Btu
Recovery		
410,000 tons @ 140,000 Btu/ton		57,400
Preparation		
Chipping - 410,000 tons @ 330,000 Btu/ton		135,300
Transportation		
Truck - 410,000 tons, 60 miles, 1730 Btu/ton-mile		42,558
	Total	235,258

TABLE 25. ENERGY CONSUMPTION FOR PATH 9, WASTE WOOD CHIPS DRIED AT THE POWER PLANT

Heating Value: 14.5 x 10^6 Btu/ton (15% M.C.) and 9.35 x 10^6 Btu/ton (45% M.C.)
Quantity Required: 363,000 tons/year of green wood = 235,000 tons/year of dried wood.

Activity	Annual Energy Consumption, 10^6 Btu
Recovery	
363,000 tons of green wood @ 140,000 Btu/ton	50,820
Preparation	
Chipping - 363,000 tons of green wood @ 330,000 Btu/ton	119,790
Transportation	
Truck - 363,000 tons of green wood, 60 miles, 1730 Btu/ton-mile	37,680
Total	208,290

TABLE 26. ENERGY CONSUMPTION FOR PATH 10, COMBINED PENNSYLVANIA BITUMINOUS - GREEN WOOD CHIP FIRING

Heating Value: Coal - 26.2×10^6 Btu/ton Tons required, 41,633
Wood - 9.35×10^6 Btu/ton Tons required, 268,363
Combined Heat Input to Boiler: 3.60×10^{12} Btu/year (Est. 29% efficiency)

Activity		Annual Energy Consumption, 10^6 Btu
Recovery		
Surface Mined Coal - Electric 92,200 Btu/ton	3,839	
Fuel and Lubricants 111,000 Btu/ton	4,621	
		8,460
Wood - Fuel 140,000 Btu/ton		37,571
Preparation		
Coal		None
Wood, chipping 268,363 tons, 330,000 Btu/ton		88,560
Transportation		
Coal - 41,633 tons, 400 miles, 680 Btu/ton-mile		11,324
Wood - 268,363 tons, 60 miles, 1730 Btu/ton-mile		27,856
	Total	173,771

It should be noted that it was unnecessary to treat the coal and, therefore, the energy losses and their costs are not incurred in the combined firing process. Likewise, the 8 percent of the total energy production consumed by stack gas cleaning is not lost nor is the sizable capital cost incurred. A relatively low energy consumption value is obtained for the combined firing paths.

Summary and Conclusions

A summary of the energy consumption balances is presented in Table 27. The table includes energy consumption values for recovery, processing, and transport of a sufficient quantity of fuel for a 50 MWe power plant in Central Vermont at a 70 percent load factor. Totals for these energy quantities for each fuel path, the path total, are given in the last column of Table 27. In comparing the energy requirements for alternate fuel paths, another important value to consider is the initial quantity of fuel required, which is shown in the first column. This value varies for the different fuel paths because of different power plant efficiencies for different fuels, or, because some fuel is lost in processing, as in the case of physical coal cleaning, or, in the case of stack gas cleaning, because of the additional power requirement to operate the scrubber. The use of green waste wood chips requires the initial procurement of more fuel than any of the other paths. Since wood is a renewable resource, this fact should not mitigate against its use. On the other hand, the green waste wood path consumes less path-total energy, which is derived from nonrenewable sources, than any of the coal paths with the exception of low-sulfur Wyoming coal.

If the wood chips were dried by means of waste heat from the power plant, the initial fuel requirement is lower than the Pennsylvania coal paths, and the path-total energy becomes even more favorable with respect to coal. The net benefits of chip drying are such that serious consideration should be given to this concept in the design of the commercial plant.

TABLE 27. SUMMARY OF ANNUAL ENERGY CONSUMPTIONS FOR TEN FUELING PATHS

Fuel Paths	Fuel Required		Recovery, 10^6 Btu			Processing, 10^6 Btu					Transportation, 10^6 Btu	Path Total, 10^9 Btu
	10^9 Btu	10^3 tons	Mining Surface	Mining Deep	Wood Waste	Physical Cleaning	Stack Gas Clean-up	Refining of Crude	Desulfurization of Residual Oil	Wood Chipping		
Low-Sulfur Wyoming Coal	3,220	170 mined	5,457								208,080	214
Pennsylvania Bituminous	3,590	137 mined		20,505		406,070					33,456	460
Pennsylvania Bituminous	3,510	134 mined		20,055			280,000				36,366	326
Pennsylvania Bituminous	3,590	137 mined	27,777			406,070					33,456	467
Pennsylvania Bituminous	3,510	134 mined	27,167				280,000				36,366	343
Caribbean Crude Oil	3,220	76									15,500	15
Domestic Crude	3,220	76						344,926	255,880		25,410	626
Green Waste Wood	3,800	410			57,400					135,300	42,558	235
Dried Waste Wood	3,400	363 (green)			50,820					119,790	37,680	208
Combined Coal/ Waste Wood	3,600	42 268	8,460		37,571					88,560	11,324 27,857	174

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(13) Personal communication, Mr. Al Miller, Marathon, Findlay, Ohio.

(14) Personal communication, Mr. Harry Morey, Total Chips, Incorporated, Sheppard, Michigan 48883, June 7, 1975.

(15) Personal communications, Mr. William Popadych, Mead Corporation, Chillicothe, Ohio, June, 1975.

(16) Personal communication, Mr. J.E. Moore, Manager Forest Programs, American Pulpwood Association, Washington, D.C., June, 1975.

(17) Unpublished report, Appendix II Energy Balance, David Camp, Department of Chemical Engineering, Massachusetts Institute of Technology, June, 1975.

(18) Personal communication, Mr. Robert Doerson, Kraft Paper Company, Hawesville, Kentucky.

COMPARATIVE COST ANALYSIS

Cost of Wood as Fuel

The fuel value of wood varies greatly with species, water content, bark content, resin content, and other factors. On the basis of heating values for wood from several sources(1,2,3)* and the approximate composition of Vermont's forest lands,(4) a heating value of 9.35 million Btu per ton of green wood (45 percent moisture) was taken as an average for Vermont woods. From some of the same sources and Wood Handbook,(5) 54 pounds per cubic foot was calculated as the average weight of green Vermont wood.

A 50-MW power plant operating at 27.4 percent efficiency with a load factor of 70 percent will require 3.80×10^{12} Btu of fuel energy per year. At 9.35×10^{6} Btu per ton, this requirement translates into about 410,000 tons of green wood per year. At 54 pounds per cubic foot, this is equivalent to 15.185×10^{6} cubic feet of green wood, or about 190,000 cords of wood per year.**

Availability of Wood as Fuel

Five counties in central Vermont (Washington, Orange, Addison, Windsor, and Rutland) contain 1,921,000 acres of commercial or potentially commercial forest land.(4) Statistics relative to growing stock and annual growth are shown in Table 28. An average acre of commercial forest land in the five counties contains 1,060 cubic feet of growing stock (Table 28) and the net annual growth throughout the state is 24 cubic feet per acre. At that rate, the regeneration time for Vermont forests is about 45 years.

Table 29 shows estimates of potential availability of green wood fuel from the five counties on a sustained-harvest (45-year cycle) basis. No differentiation is made as to ownership of the forest land, whether it be private, corporate, Green Mountain National Forest, or

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* References are listed on Page 161.

** A cord is considered to be equivalent to 80 cubic feet of solid wood, excluding bark.

TABLE 28. FOREST LANDS IN FIVE COUNTIES IN CENTRAL VERMONT

	Addison	Orange	Rutland	Washington	Windsor	Total
Total land area, 1000 acres	501.5	441.7	593.3	452.8	617.8	2,607
Commercial forest land area, 1000 acres	285.8	335.9	444.9	361.3	492.6	1,920.5
Softwood types, 1000 acres	69.5	140.2	104.5	137.1	123.6	575
Hardwood types, 1000 acres	216.3	195.7	340.4	224.2	369.0	1,346
Growing stock, 10^6 ft^3	276.5	352.4	462.8	404.8	540.7	2,037
Softwood, MM 10^6 ft^3	68.7	162.9	119.3	176.5	151.2	679
Hardwood, MM 10^6 ft^3	207.8	189.5	343.5	228.3	389.5	1,358
Growing stock, ft^3/acre	967	1,049	1,040	1,120	1,098	1,060
Annual growth$^{(a, b)}$						
Gross, 1000 ft^3	11,758	13,819	18,303	14,864	20,266	79,010
Cull, 1000 ft^3	2,938	3,453	4,574	3,714	5,064	19,743
Mortality, 1000 ft^3	1,941	2,281	3,021	2,453	3,345	13,040
Net annual growth, 1000 ft^3	6,879	8,085	10,709	8,696	11,857	46,226

Source: Reference 4.

a. Volumes of growing stock and annual growth are expressed as cubic feet of sound wood in the bole from a 1-foot (height) stump to a 4-inch (diameter) top outside the bark (or to where the main stem branches) of all commercial species trees at least 5-inch dbh (diameter at breast height).

b. These increments of annual growth were calculated for the five counties on the basis of the following volumes for all of Vermont, as given in Reference 4:

	Net Cubic Feet/Acre
Gross growth	41.14
Cull increment	10.28
Mortality	6.79
Net growth	24.07

Cull increment is the volume of trees that were classified as growing stock at the beginning of the measurement period but were too poor in quality at the end of the period to be so classified.

Mortality is the volume of growing-stock trees that have died since the beginning of the measurement period.

Net annual growth is gross growth minus cull increment and mortality.

TABLE 29. POTENTIAL AVAILABILITY OF GREEN WOOD FUEL FROM FIVE VERMONT COUNTIES(a) ON A SUSTAINED-HARVEST BASIS

	Green Wood Available from Annual Growth on 1,920,500 Acres				
	Net Growing Stock(b)	Harvest(c)	Harvest Residue(d)	Culls and Dead Trees(e)	Total(f)
Volume, 10^6 ft^3	46.226	43.915	8.783	26.102	78.800
1000 Cords (80 ft^3/cord)	578	549	110	326	985
Weight, 1000 tons(g)	1,248	1,186	237	705	2,128

a. Addison, Orange, Rutland, Washington, and Windsor Counties contain 1,920,520 acres defined as commercial forest land.

b. From Table 28.

c. Merchantable bole estimated as 95 percent of full tree bole on the basis of information contained in Reference 6.

d. Slash (top, branches, and foliage) estimated as 20 percent of harvestable bole on the basis of information contained in Reference 6.

e. Table 28 shows volume of cull trees to be 19.743 million cubic feet of full tree bole. Slash from cull trees would be $19.743 \times 10^6 \times 0.95 \times 0.20 = 3.751\ ft^3$. Total fuel volume would be $(19.743 + 3.751)10^6 = 23.494 \times 10^6\ ft^3$. Table 28 also shows volume of trees that have died since 1966 to be 13.040 million ft^3. If 20 percent of this tree volume is useful for fuel, it would add another 2,608 million ft^3, bringing the total fuel volume for culls and dead trees to 26.102 million cubic feet.

f. Total includes harvest, harvest residue, culls and dead trees.

g. Based on average of 54 pounds per cubic foot of green wood.

other. It can be seen from Table 29 that complete harvesting for fuel equivalent to the annual growth of merchantable wood, tree residues, and culls and dead trees throughout the five counties would yield about 2,128,000 tons of green wood, or about five times the requirement for a 50-MW power plant. This usage of the entire annual growth for fuel would be uneconomic, because it ignores the much higher value of harvestable sawlogs and poles.

If harvesting for fuel were limited to salvaging the residues from conventional timber harvesting and removal of culls and dead trees, the five counties could yield annually about 942,000 tons of green fuel wood, or about 2.3 times the fuel requirements of a 50-MW power plant. This appears to indicate that adequate green wood to fuel the power plant should be available within a radius of about 25 miles. To the extent that actual clearcutting is practiced and saplings less than 5 inch dbh* are used, that radius could be reduced.

The preceding estimate is based on harvesting green wood equivalent to 100 percent of the net annual growth within a radius of 25 air miles from the proposed power plant. In 1972, the total wood harvested in all of Vermont was only 45 percent of the net annual growth.(4) If this harvesting percentage is applicable to central Vermont and if it persists despite the need for fuel for a 50-MW power plant, the harvesting area would have to be increased to a radius of 35 air miles from the plant.

It is not clear why only 45 percent of the net annual growth of Vermont's commercial forest lands was harvested in 1972, in sharp contrast with 71 percent in 1948 and 74 percent in 1966.(7) Possible reasons may include reduced markets available to Vermont wood, reduced availability of forest workers, and inadequate stumpage prices to be attractive to owners. On the assumptions that stumpage prices will be attractive to owners, markets will exist for Vermont sawlogs and poles, and adequate woodsmen will be available, it is estimated that adequate green wood fuel to operate a 50-MW power plant will be available on a 45-year cycle from harvest residues and dead and cull trees within 30 air miles of the plant. The average hauling distance should be about 25 miles and the maximum about 45 miles.

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* dbh - Diameter at breast height (4 feet).

Wood Fuel Procurement Costs

Stumpage costs vary considerably with the value of wood being harvested and the difficulty of harvesting. An average figure for Vermont is said to be \$2 per cord.(8) At 80 cubic feet per cord and 54 pounds per cubic foot for green wood, this figures to be \$0.93 per ton. By 1980, if inflation averages 7 percent per year, this value would be \$1.30 per ton. However, this is the value paid for the privilege of harvesting valuable sawlogs and poles, although the harvest may, in some cases, include the conversion of woodland residues to pulpwood chips. More commonly the residues are left to decay on the forest floor (returning nutrients to the soil) or are piled and burned (also returning nutrients to the soil).

Although not widely practiced in Vermont, the removal of dead and cull trees for stand improvement costs the landowner about \$25 per acre. In this practice, the wastes are left to decay on the forest floor. Some landowners may be willing to trade the value of future nutrients against current improvement costs and permit the removal of dead and cull trees at no stumpage cost.

It is estimated that the equivalent of stumpage costs for collecting harvesting residues and dead and cull trees in 1980 will be about \$0.50 per ton. This stipend, added to stumpage for conventional harvesting, would increase fees paid to the landowner for multiple harvest by about 40 percent over the normal fees. This might be the inducement needed to assure the continued availability of adequate fuel resources within about 30 miles of the plant. Even if it were necessary to triple this price to assure the availability of wood fuel, it would increase the overall cost of the fuel by only about 12 percent.

Cost of Harvesting Wood Fuel

Timber in Vermont is currently harvested exclusively by chainsaw and operator. There has been at least one experiment with mechanical harvesting and total tree chipping in New Hampshire,(9) but it does not seem likely that mechanical harvesting will soon make much inroad in Vermont's forests.

Table 30 shows certain 1970 Census Bureau financial data for SIC 24, Lumber and Wood Products, for New England and for Vermont, and similar data for SIC 2411, Logging Camps and Logging Contractors, for New England.(10)* On the assumption that logging operations in Vermont bear the same relationship to the lumber and wood products industry that they do in New England as a whole, comparable figures for Vermont's logging industry were calculated and these also are shown in Table 30.

Comparable 1972 data are available for New England but not for Vermont.(11) These data for logging camps and logging contractors are combined in Table 31 with 1970 data for New England and Vermont to facilitate calculation of appropriate 1972 data for logging operations in Vermont.

In 1972, 47 million cubic feet of growing stock were harvested in Vermont's forests. At 95 percent recovery of full tree bole as sawlogs and poles, this represents 44.65 million cubic feet of merchantable wood. From this figure and the estimates of costs shown in Table 31 for 1972, it was possible to calculate the incremental costs of harvesting wood in Vermont, as shown in the following tabulation:

	$\$/Ft^3$, 1972	\$/Ton 1972	\$/Ton 1975(a)
Payroll	0.0708	2.62	3.30
Cost of materials	0.1832	6.79	8.55
Taxes, profits, etc.	0.0862	3.19	4.02
Value of shipments	0.3402	12.60	15.87

(a) Based on inflation at 8 percent per year

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* No data are given for SIC 2411 in Vermont. Data for 1971 could have been used, but Vermont figures for SIC 24 are marked with an asterisk, implying a low degree of reliability.

TABLE 30. FINANCIAL DATA, 1970, LUMBER AND WOOD PRODUCTS, FOR NEW ENGLAND AND VERMONT

	Millions of Dollars		
	Payroll	Cost of Materials	Value of Shipments
Lumber and Wood Products			
New England	133.1	240.5	482.6
Vermont	13.4	22.1	48.2
Logging Camps, Contractors			
New England	29.2	73.3	130.4
Vermont	2.94(a)	6.74(a)	13.02(a)

Source: Annual Survey of Manufactures (Reference 10).

(a) Figures for Vermont logging camps calculated as a ratio with figures for New England. For example, for Payroll:

$$\frac{13.4}{133.1} \times 29.2 = 2.94.$$

TABLE 31. FINANCIAL DATA, 1970 AND 1972, LOGGING CAMPS AND LOGGING CONTRACTORS, FOR NEW ENGLAND AND VERMONT

	Millions of Dollars			
	Payroll	Materials	Interest, Taxes, Profit, etc.(a)	Value of Shipments
New England				
1970	29.2	73.3	27.9	130.4
1972	31.4	89.0	31.7	152.1
Vermont				
1970	2.94(b)	6.74(b)	3.34	13.02(b)
1972	3.16(c)	8.18(c)	3.85	15.19(c)

Sources: 1970 New England data from Reference (10).
1972 New England data from Reference (11).

a. Interest, taxes, profit, etc. derived by subtracting payroll and cost of materials from value of shipments.

b. 1970 Vermont data calculated by Battelle (see Table 30).

c. 1972 Vermont data calculated by Battelle as in Footnote (a), Table 30.

This harvesting cost of $15.87 per ton of wood is misleading as a cost of harvesting green wood for fuel. It includes stumpage fees, which were earlier estimated at $0.93 per ton of green wood. Deducting this cost leaves a cost of $14.34 per ton for actual harvesting costs. Furthermore, the harvesting of timber boles includes the handling of approximately 20 percent of slash and a significant quantity of dead trees, from which some timber is recovered.

It is estimated that the cost of collecting timber residues, cull trees, and dead trees in conjunction with, but as a separate operation from, conventional harvesting, would be only about 50 percent of the cost of conventional harvesting. The use of full-tree chippers in the field means that most of the cutting would be limited to felling cull trees and dead trees from which no timber was harvested. Most of the cost would be concerned with bunching and skidding material to the chipper. Under these conditions, it is estimated that the cost in 1975 of harvesting green fuel wood in Vermont would be about $7.60 per ton, exclusive of any stumpage costs. By 1980, if inflation averages 7 percent per year, harvesting costs would be $10.65 per ton of green fuel wood.

Chipping Costs

An average acre of commercial forest land in central Vermont contains 1,060 cubic feet of growing stock, equivalent to 28.62 tons of harvestable green timber. The residues from harvesting this timber plus culls and dead trees would amount to about 22.75 tons per acre (see Table 29). Based on experience of an in-forest chipping operation in Michigan, a chipper can operate economically within a radius of about 1/4 mile, or an area of about 125 acres, before moving to a new location.(12) Approximately 2,850 tons of chips could be produced before the chipper was moved. The Michigan chipper averaged 200 tons of green chips per day or 1000 tons per week, including all down time for maintenance, repairs, moves, etc. On this basis, a chipper in Vermont would move to a new location about every 3 weeks.

A 50-MW power plant would require 410,000 tons per year of green wood fuel or about 7900 tons per week. If chippers could operate 260 days per year, eight chippers would be required to fill this need. Because of days lost to inclement weather, ten or more chippers would be required.

In the New Hampshire experiment in total tree chipping in the forest, five men were required in the yard, including the chipper operator.(9) At $3 per hour for 1975 wages, plus 8 percent for management, this would require a payroll of $650 per week.

In the Michigan experience in 1974, operating costs for the yard machinery and chipper, including blowing chips into trucks, but exclusive of labor, were $777 per 1000 tons of chips, including interest, taxes, etc.(12)

The cost of in-forest chipping in 1975 is thus estimated at $1427 per thousand tons, or $1.43 per ton of green chips. By 1980, at 7 percent inflation per year, that cost would be $2.01 per ton.

Transportation Costs

The transportation of chips is best accomplished by truck, preferably a tractor-trailer with nondumping box. Chips are blown in at the chipper and the box is unloaded by small front-end loaders, or after detachment from the tractor, by a tilting platform.

The going rate for hauling chips appears to average about $0.05 per ton mile. With an average hauling distance of 25 miles, hauling charges in 1975 should average about $1.25 per ton. Inflating this value by 7 percent per year gives a hauling cost of $1.75 per ton in 1980.

Replacement of Soil Nourishment

This subject is little understood and less practiced. In normal woodland harvesting, residues are either allowed to decay on the forest floor or are piled and burned. In either case, most of the inorganic chemical content of the residues is returned to the soil, although much nitrogen content is lost, particularly when residues are burned. The inorganic material that is hauled away in wood products is completely removed from the forest.

A recent study in Wisconsin delineated the amounts of nitrogen, phosphorus, potassium, and calcium removed from the forest by whole-tree harvesting of a 40-year-old aspen-mixed hardwood second-growth forest.(13) Virtually all trees larger than 1 to 2 inches in diameter were harvested by a feller-buncher. A total of 111,386 pounds (55.693 tons) of wood products per acre were removed as chips, sawlogs, waste, and bark. Elemental analyses were made of the wood products and the following nutrient losses were calculated:

	Wisconsin	
Elements Removed	Pounds Per Acre	Pounds Per Ton of Wood Product
Nitrogen	172	3.09
Phosphorus	24	0.43
Potassium	116	2.08
Calcium	382	6.86

The same authors estimated that inputs of nitrogen, phosphorus, and potassium during the next 30 years from precipitation, mineralization, and weathering would more than balance the amounts of those nutrients removed at their particular Wisconsin location. The return of calcium was estimated to be slightly insufficient, such that the calcium reserve in the soil would support only nine 30-year cycles, and modest addition of lime would be required.

With a 45-year regeneration cycle, Battelle believes that the inputs of nutrients to Vermont's forest lands will compensate for nutrients removed by multiple harvest. However, it is interesting to see what the cost of such nutrients might be if they had to be replaced.

It was stated earlier that the average harvest of timber in Vermont would be about 28.62 tons per acre and the average collection of green wood accompanying such harvest about 22.75 tons per acre. Applying the findings in the Wisconsin investigation to the Vermont situation, the following amount of nutrients would be removed by multiple harvesting:

Nutrient Element	Pounds Removed Per Acre in Harvesting Vermont Forests		
	Primary Harvest	Fuel Harvest	Total Harvest
Nitrogen (N)	90	70	160
Phosphorus (P_2O_5)	12	10	22
Potassium (K_2O)	60	47	107
Calcium (CaO)	196	156	352

Fertilizer prices are published periodically by the U.S. Department of Agriculture.(14) The following tabulation shows fertilizer ingredient prices in Vermont in April, 1975, from which the cost per pound of the various nutrients is calculated:

Fertilizer Ingredient	Vermont, April, 1975		
	Price, $/ton	Nutrient	
		lb/ton	$/lb
Urea, 45.5% N	290	910	0.3187
Superphosphate, 20% P_2O_5	135	400	0.3375
Potash, 60% K_2O	135	1200	0.1125
Limestone, 47% CaO	20*	940	0.0213*

Figures from these two tabulations were used to calculate the 1975 cost of nutrients removed from Vermont forest lands by multiple harvest. These costs are shown in Table 32. The cost of buying fertilizer materials to replace the removed nutrients would be about $1.45 per ton of wood, with perhaps an additional $0.50 per ton of wood as the cost of application. As mentioned earlier, Battelle believes that these nutrients will be restored naturally, and the cost of fertilization is not included in the sustained-harvest cost of wood fuel.

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* For limestone, price includes cost of application.

TABLE 32. COST OF NUTRIENTS REMOVED BY MULTIPLE HARVEST IN VERMONT'S FOREST LANDS

Nutrient	Dollars Per Acre Primary Harvest	 Fuel Harvest	 Total	Dollars Per Ton of Wood
Nitrogen (urea)	28.68	22.31	50.99	1.00
Phosphorus (superphosphate)	4.05	3.38	7.43	0.14
Potassium (potash)	6.75	5.29	12.04	0.24
	39.48	39.98	70.46	1.38
Calcium (limestone)	1.96(a)	1.56(a)	3.52(a)	0.07(a)

(a) For limestone, cost includes cost of application.

Power Plant Costs Using Wood Fuel

The operating costs of a power plant include costs of the basic plant, fuel, operations and maintenance, emission controls, cooling facilities, water, water conveyance, and transmission. For the hypothetical 50-MW power plant in central Vermont, some of these factors would be constant regardless of fuel, but difficult to determine without a detailed, site-specific study. Consequently, estimates of power plant nonfuel costs for burning the various fuels to generate electricity include annual costs of the basic plant (once-through water cooling), emission controls, and operation and maintenance, but do not include costs of water, water conveyance, and transmission of electricity. Table 33 shows estimated costs of burning coal, oil, and wood in a 50-MW power plant in 1980. The method for estimating these costs is discussed in the following paragraphs.

Petruschell and Salter compared 1972 costs of nuclear, coal, oil, and natural gas power plants and projected these costs to 1985.(15) They found the average capital investment for a 1000-MW coal plant in 1972 to be $143 million, and that for a 1000-MW oil plant to be $139 million. Annual costs associated with these investments for a 70 percent load factor would be $39.2 million for coal and $36.1 million for oil. Using the 0.6 factor to adjust for plant size and escalating costs by 7 percent per year, the capital investment in 1980 for a 50-MW coal plant should be $40.7 million and that for an oil plant should be $39.5 million. Annual costs for a coal plant should be $6.50 million and those for an oil plant $5.99 million. Battelle estimates the 1980 capital investment for a 50-MW wood-fired plant to be $40 million and the annual cost to be $6.23 million.

Emission control costs are far from being firmly established. McGlamery and Torstrick examined investment and operating costs for a variety of flue gas desulfurization processes, including particulate removal.(15a) Based on 1974 construction costs and estimated 1975 operating costs, they estimated a capital cost of $27,452,000 and an average annual cost of $8,101,900 for a typical lime slurry process for a new 500-MW plant burning coal containing 3.5 percent sulfur. Adjusting for plant

TABLE 33. ESTIMATED COSTS OF BURNING VARIOUS FUELS IN A 50-MW POWER PLANT - 1980

	$, million		
	Capital Investment	Annual Cost	Mills/kwh
Basic Plant			
Coal	40.6	6.50	21.2
Oil	39.5	5.97	19.5
Wood	40.0	6.24	20.4
Emission Control			
Coal (SO_2 plus particulates)	10.4	2.85	9.3
Low-sulfur coal (particulates)	3.5	0.97	3.2
Oil (particulates)	3.1	0.86	2.8
Wood (particulates)	2.5	0.69	2.3
Dual, wood/low-sulfur coal (particulates)	3.5	0.97	3.2
Operation and Maintenance	--	0.71	2.33

size and escalating costs at 7 percent per year, the capital investment in 1980 for emission control for a 50-MW coal plant should be $10.4 million and the annual cost should be $2.85 million. Battelle estimates the 1980 investment for emission control for a 50-MW oil plant (particulates only) will be $3.1 million and for a similar wood plant (particulates only) will be $2.5 million. Annual costs will be $860,000 for oil and $690,000 for wood.

Operation and maintenance costs should be essentially the same for coal-fired, oil-fired, or wood-fired plants. On the basis of information derived from Petruschell and Salter,(15) these costs in 1980 for a 50-MW plant should average $710,000.

The cost (within the plant) of generating electricity with a particular fuel is the sum of the annual costs for plant, emission control, and operation and maintenance factors. For a 50-MW wood-burning plant, the annual cost in 1980 of these factors from Table 33 is $7.63 million.

Summary of Wood Fuel Costs

The various cost elements of producing and burning wood to generate electricity in a 50-MW power plant in central Vermont are summarized in Table 34.

Costs of Various Coal Fuels

The 50-MW power plant in central Vermont might be fired with other fuels under conditions that would meet environmental standards. The alternative fuel systems to be considered here are low-sulfur coal, physically cleaned coal from Pennsylvania, and high-sulfur coal with stack gas desulfurization.

Low-Sulfur Coal

The nearest reliable source of low-sulfur coal to Vermont is subbituminous coal in Wyoming. This coal contains less than 1 percent sulfur and has an average heating value of 19 million Btu per ton.

TABLE 34. THE COST OF WOOD AS A FUEL TO GENERATE ELECTRICITY IN VERMONT - 1980

Cost Element	Cost $/ton	 $/year[(a)]	 Mills/kwh
Procurement (stumpage)	0.50	204,800	0.67
Harvesting	10.65	4,366,500	14.24
Chipping	2.01	824,100	2.68
Transportation	1.75	717,500	2.34
Basic plant	--	6,230,000	20.32
Emission control	--	690,000	2.25
Operation and maintenance	--	710,000	2.32
Total	14.91	13,743,000	44.82

(a) A 50-MW power plant operating at 70 percent load factor requires 410,000 tons of green wood per year.

Mining Costs. Most Wyoming coal is recovered by strip mining. The U.S. Bureau of Mines estimated capital investment, operating costs, and selling price for a strip mine in the Northern Great Plains as of May, 1974.(16) This hypothetical mine was based on production of 9.2 million tons per year, with a life span of 20 years and a discounted cash flow of 12 percent. The Bureau estimated initial capital investment at $29,871,000 and total capital investment at $56,286,000. The operating cost for such a mine was estimated at $2.27 per ton and the selling price of the coal at $2.66 per ton.

The actual prices of several deliveries of Wyoming coal to nearby electric utilities (in the same or adjacent county as the strip mine) averaged $3.97 per ton from February through April of 1975.(17) This figure was taken as the average FOB price of strip-mined Wyoming subbituminous coal delivered to the rather sparse railroads. If coal is to fill the energy need projected for it during the coming decades, it seems likely that coal costs will increase by at least 10 percent per year through 1980. At this inflation rate, the FOB price for Wyoming strip-mined subbituminous coal should be about $6.40 per ton by 1980.

Shipping Costs. Battelle has found no record of shipments of Wyoming coal to New England. Freight costs vary considerably with type of shipment (unit train, complete train load, single car), size of shipment, distance, geographical area, and time (seven rate increases from January 1, 1974, to June 8, 1975). On the basis of a comprehensive study of shipping costs, the U.S. Bureau of Mines estimated the 1970 cost for shipping coal from Cheyenne, Wyoming, to Boston, Massachusetts, under "best practice" conditions (shipment greater than 80,000 tons) was $0.523 per million Btu.(18) At 19 million Btu per ton, this would be $9.94 per ton for Wyoming subbituminous coal. The Bureau also estimated an average increase of $1.40 per ton for shipments less than 8000 tons, bringing the average freight cost to $11.34 per ton. Battelle estimates the additional cost of routing the shipment to central Vermont would bring the 1970 freight to $12 per ton. The various ex parte freight rate increases since 1970 bring the current average rate from Wyoming to central Vermont to $19.25 per ton.

An approach to estimating escalation of shipping costs based on correlating elements of operating costs to the GNP deflator for the period from 1960 to 1973 was used by Aude, et al.(19) in comparing slurry-pipeline systems with railroad systems for moving various solids. At a general inflation rate of 7 percent per year, the escalation for rail freight costs would be 11.9 percent per year. This escalation rate checks very well for the period 1972 to 1975 ($19.25/ton versus $19.45/ton with actual ex parte rate increases). Applying the same rate of escalation to the $19.45 freight for 1975 gives $34.12 per ton for 1980.

Power Plant Costs. The information derived from Petruschell and Salter(15) and McGlamery and Torstrick(15a) was used to estimate the nonfuel cost of generating electricity with low-sulfur coal as in the section on Power Plant Costs Using Wood Fuel. The capital investment in 1980 for a 50-MW plant burning low-sulfur coal should be about the same as that for a typical coal plant, or about $40.7 million. However, the investment for emission controls should be about $3.5 million.

Annual costs in 1980 for a 50-MW plant burning low-sulfur coal and operating at a 70 percent load factor should be about $6.5 million for the basic plant and $970,000 for emission control, or about $8.2 million for plant, emission control, and operations and maintenance.

Summary of Low-Sulfur Coal Costs. The various cost elements associated with using low-sulfur subbituminous coal from Wyoming to generate electricity in a 50-MW power plant in central Vermont are summarized in Table 35.

Physically Cleaned Coal

The most likely candidates as sources of high-sulfur coal that can effectively be physically cleaned are the upper and lower Kittanning and upper and lower Freeport beds in southwestern Pennsylvania. Coal

TABLE 35. THE COST OF LOW-SULFUR COAL FROM WYOMING TO GENERATE ELECTRICITY IN VERMONT - 1980

Cost Element	Cost $/ton	 $/year[(a)]	 Mills/kwh
Mining	6.40	1,088,000	3.55
Transportation (rail)	34.12	5,800,400	18.92
Basic plant	--	6,500,000	21.20
Emission control	--	970,000	3.16
Operation and maintenance	--	710,000	2.32
Total	40.52	15,068,000	49.15

(a) A 50-MW power plant operating at 70 percent load factor requires 170,000 tons per year of low-sulfur coal having a heating value of 19 million Btu/ton.

losses ranging from 10 percent to 50 percent accompany physical cleaning of coal. In the five Pennsylvania counties in which these coal beds are mined most extensively, losses on cleaning coal from about 3 percent sulfur to 1 percent or less average about 20 percent of the original coal. However, the Kittanning and Freeport coals in these counties average only about 1.7 percent sulfur. Battelle believes the losses incurred in cleaning such coals to approximately 0.7 percent sulfur will not exceed 10 percent.

Mining Costs. About 65 percent of the bituminous coal produced in Pennsylvania comes from deep mines. Furthermore, 95 percent of the State's reserves (28 inches or more in thickness to a maximum depth of 1000 feet) are in deep seams, and only 5 percent are recoverable by surface mining. Consequently, the cost of Pennsylvania coal is high and prospects are that it will continue to be high.

The U.S. Bureau of Mines estimated 1973 capital investments, operating costs, and selling prices for several sizes of underground bituminous coal mines operating in 72-inch coal beds.(20) For a mine producing 1.06 million tons per year, they estimated an initial capital investment of $12,541,000 and a total capital investment of $21,851,000. With a life of 20 years and assuming a 12 percent discounted cash flow, they estimated operating cost at $7.35 per ton and selling price at $8.76 per ton.

The actual prices of 31 deliveries of western Pennsylvania coal to nearby electric utilities (within the same county) from January through May of 1975 averaged $20.30 per ton. This figure was taken as the average price of coal delivered to a coal cleaning plant, although the increment for local transportation might actually be made after cleaning rather than before. By 1980, at 10 percent escalation per year, this price for mined and locally delivered coal, would be about $32.70 per ton.

Cleaning Costs. The hypothetical 50-MW power plant in central Vermont will require 123,000 tons of cleaned Pennsylvania coal per year at

26.2 million Btu per ton and containing 0.7 percent sulfur. With a 10 percent loss on cleaning, this will require a feed of 137,000 tons per year of coal containing 1.7 percent sulfur, or 570 tons per day (240 working days per year). At 40 hours operation per week, a plant of this size would not be very economic. Although cleaning plants of such a size exist, they are generally not equipped adequately to do as good a job of cleaning as is required here.

A cleaning plant that will handle 600 tons per hour of raw coal should be equipped to do economically the required cleaning job. On the basis of a study done at Battelle in 1974, the capital cost of a 600-ton-per-hour physical cleaning coal plant in 1974 was $7.88 million. On the basis of a coal feed containing 24 million Btu per ton, a loss of 15 percent, and a price for raw coal of $12 per ton, a cleaning cost of $0.14 per million Btu or $3.36 per ton was found. Adjusting these costs for the coal under consideration in this report (26.2 million Btu per ton, 10 percent loss on cleaning, $20 per ton for raw coal) gives a current cost of $0.17 per million Btu or $4.45 per ton for cleaning. At 9 percent escalation per year (a compromise between coal at 10 percent and general economy at 7 percent), the cost in 1980 for cleaning coal would be about $6.85 per ton.

Shipping Costs. Utilizing information published by the U.S. Bureau of Mines(18) and Aude, et al.(19) and the technique discussed in the subsection on Shipping Costs in the section on Low-Sulfur Coal, Battelle estimates the average cost for shipping coal from western Pennsylvania (District 2) to Vermont is currently $13.38 per ton. By 1980, this cost should be $23.48 per ton.

Power Plant Costs. The method described in the section on Power Plant Costs Using Wood Fuel, based on information published by Petruschell and Salter(15) and McGlamery and Torstrick(15a), was used to estimate the nonfuel cost of using cleaned coal (0.7 percent sulfur) to generate electricity. The capital investment in 1980 for a basic 50-MW plant burning physically cleaned coal should be about the same as that for a typical basic coal plant, or about $40.7 million. The gaseous effluent from burning coal with a sulfur content of 0.7 percent and with a heating value of 26.2 million Btu per ton will not exceed the limit on sulfur oxide emissions (1.2 pounds SO_2 per million Btu) imposed by the Clean Air Act of 1970 on fossil fuel-burning equipment started after August 17, 1971, and having a capacity of more than 250 million Btu, which is equivalent to 1.15 pounds of SO_2 per million Btu. Battelle estimates the investment for particulate emission control should be about $3.5 million.

Annual costs in 1980 for a 50-MW plant burning physically cleaned coal and operating at a 70 percent load factor should total about $8.2 million for the basic plant, emission control, and operation and maintenance.

Summary of Cleaned Coal Costs. The various costs associated with using physically cleaned bituminous coal from western Pennsylvania to generate electricity in a 50-MW power plant in central Vermont are summarized in Table 36.

High-Sulfur Coal with Stack Gas Cleaning

The sulfur content of coal mined in west central Pennsylvania ranges generally between 2.8 percent and 4.5 percent and the heating value ranges from 24 million to 26 million Btu per ton. An average sulfur content of 3.3 percent and heating value of 25 million Btu per ton were assumed. Although this coal from District 1 is less amenable to physical cleaning than the Kittanning and Freeport coals from District 2, it is located a little closer to Vermont and transportation costs will be a little lower.

Mining Costs. Mining costs of the bituminous coal from District 1 should be essentially the same as those from District 2. Consequently, the price of coal delivered to a railroad loading facility in the same county should average about $32.70 per ton by 1980.

TABLE 36. THE COST OF USING CLEANED PENNSYLVANIA BITUMINOUS COAL TO GENERATE ELECTRICITY IN VERMONT - 1980

Cost Element	Cost $/ton	 $/year[(a)]	 Mills/kwh
Mining	32.70	4,022,100	13.12
Cleaning	6.85	842,550	2.75
Transportation (rail)	23.41	2,880,000	9.39
Basic plant	--	6,500,000	21.20
Emission control	--	970,000	3.16
Operation and maintenance	--	710,000	2.32
Total	62.96	15,925,000	51.94

(a) A 50-MW power plant operating at 70 percent load factor requires 123,000 tons per year of physically cleaned coal having a heating value of 26.2 million Btu/ton.

Shipping Costs. Using the same sources(18,19) and technique used in the earlier estimates of shipping costs, Battelle estimates the average cost for shipping coal from west central Pennsylvania (District 1) to Vermont is currently \$12.69 per ton and will be \$22.26 per ton by 1980.

Power Plant Costs. Using the same sources(15,16) and technique used in the earlier estimates of nonfuel costs of generating electricity, the cost was estimated for burning high-sulfur coal and employing stack gas cleaning. The capital investment in 1980 for a basic 50-MW plant burning high-sulfur coal should be about \$40.7 million. However, the investment for emission control (sulfur oxides and particulates) should be about \$10.4 million.

Annual costs in 1980 for a 50-MW plant burning high-sulfur coal and operating at a 70 percent load factor should be about \$6.5 million for the basic plant, \$2.85 million for emission control, and \$710,000 for operation and maintenance.

Summary of High-Sulfur Coal Costs. The various costs associated with using high-sulfur bituminous coal from west central Pennsylvania with stack gas cleaning to generate electricity in a 50-MW power plant in central Vermont are summarized in Table 37.

Dual System - Green Wood Plus Cleaned Coal

It is possible that fresh supplies of green wood fuel could be shut off for weeks or even months at a time. In such an event, it would be desirable to have a system that could burn wood or coal interchangeably. For this analysis, it will be assumed that 75 percent of the annual Btus will be provided by green wood and 25 percent by physically cleaned coal.

Wood Fuel Costs. About 308,000 tons of green wood will be required annually to provide 75 percent of the heat requirement for a 50-MW power plant operating at 70 percent load factor. It is anticipated that the cost per ton for this wood will be the same as the cost per ton for

TABLE 37. THE COST OF USING HIGH-SULFUR PENNSYLVANIA BITUMINOUS COAL WITH STACK GAS CLEANING TO GENERATE ELECTRICITY IN VERMONT - 1980

Cost Element	Cost		
	\$/ton	\$/year[(a)]	Mills/kwh
Mining	32.70	4,218,000	13.76
Transportation	22.26	2,871,500	9.37
Basic plant	--	6,500,000	21.20
Emission control	--	2,850,000	9.30
Operation and maintenance	--	710,000	2.32
Total	54.96	17,150,000	55.94

(a) A 50-MW power plant operating at 70 percent load factor requires 129,000 tons per year of high-sulfur coal having a heating value of 25 million Btu per ton.

wood to supply 100 percent of the heat requirement for the power plant.

Physically Cleaned Coal Costs. About 31,000 tons of physically cleaned coal will be required annually to provide 25 percent of the heat requirement for a 50-MW power plant operating at 70 percent load factor. This is not a sufficient quantity of coal to attract a favorable contract price. Battelle estimates the cost per ton for mining and cleaning this small amount of coal will be about 10 percent higher than the costs would be if cleaned coal were the only fuel used.

Power Plant Costs. The cost of a power plant to burn wood or coal interchangeably will be somewhat greater than the cost of a power plant to burn either fuel solely. Dual capabilities will be required for receiving, storage, and conveyance of the fuels to a fuel hopper or feeder. Fuel feeding and burning capabilities must be sufficiently flexible to handle either high-volume, low-density wood fuel or low-volume, high-density coal. Probably a spreader-stoker firing system with water-cooled grate would be employed, and ash handling capabilities would have to be sufficient to handle 100 percent coal firing. Particulate control would have to be sufficient to handle 100 percent wood firing, but no other emission controls would be required.

Battelle estimates the 1980 capital investment for a 50-MW dual-fired (wood and cleaned coal) plant will be $40.9 million and the annual cost will be $6.65 million. The investment for emission controls will be about $3.5 million and annual costs will be about $970,000.

Summary of Fuel System Costs. The various costs associated with burning green wood and physically cleaned coal interchangeably to generate electricity in a 50-MW power plant in central Vermont are summarized in Table 38.

TABLE 38. THE COST OF USING GREEN WOOD AND PHYSICALLY CLEANED COAL INTERCHANGEABLY TO GENERATE ELECTRICITY IN VERMONT - 1980

Cost Element	Cost		
	\$/ton	\$/year[(a)]	Mills/kwh
Procurement (stumpage)	0.50	154,000	0.50
Harvesting	10.65	3,280,000	10.70
Chipping	2.01	619,000	2.02
Transportation (truck)	1.75	539,000	1.76
Mining	35.97	1,115,000	3.64
Cleaning	7.54	234,000	0.76
Transportation (rail)	23.41	726,000	2.37
Basic plant	--	6,650,000	21.70
Emission control	--	970,000	3.16
Operation and maintenance	--	750,000	2.45
Total		15,037,000	49.06

(a) Assumes 75 percent of annual heat requirement will be provided by wood and 25 percent by cleaned coal. A 50-MW power plant operating at 70 percent load factor will require 308,000 tons of green wood and 31,000 tons of cleaned coal per year.

Comparison of Various Solid Fuel Costs

Table 39 shows the estimated costs of using wood in Vermont to fire a 50-MW power plant in 1980 compared with similar costs for using low-sulfur subbituminous coal from Wyoming, cleaned bituminous coal from Pennsylvania, high-sulfur bituminous coal from Pennsylvania with stack gas cleaning, and a dual system comprising 75 percent wood and 25 percent cleaned coal.

If all of the assumptions made in this analysis are valid, it appears that the use of green wood fuel to generate electricity in Vermont is economically feasible.

Sensitivity of Power Generation Costs to Changes in Costs of Various Inputs

The effects on power generation costs of 25 percent increases and 25 percent decreases in fuel costs, transportation costs, emission control costs, and plant sizes were determined for 50-MW power plants in central Vermont burning green wood, low-sulfur coal, cleaned coal, high-sulfur coal with stack gas cleaning, and 75 percent green wood, 25 percent cleaned coal.

Effect of Changing Fuel Costs

The calculated impacts of 25 percent increases and decreases of the various fuel costs on the costs of power generation are shown in Table 40. Generation cost at the wood-fired plant is most sensitive to changes in fuel costs and that at the plant fired with low-sulfur fuel is least sensitive.

Effect of Changing Transportation Costs

The calculated impacts of 25 percent increases and decreases in transportation costs on the costs of power generation are shown in Table 41. Generation cost at the wood-fired plant is least sensitive to changes in transportation costs and that at the plant fired with low-sulfur coal

TABLE 39. THE ESTIMATED COSTS OF USING VARIOUS FUELS TO GENERATE ELECTRICITY IN VERMONT - 1980

Cost Element	Green Wood		Low-Sulfur Coal (Wyoming),		Cleaned Coal (Pennsylvania),		High-Sulfur Coal Stack Gas Cleaning (Pennsylvania),		75% Green Wood 25% Cleaned Coal,	
	$M/year	Mills/kwh	$M/year	Mills/kwh	$M/year	Mills/kwh	$M/year	Mills/kwh	$M/year	Mills/kwh
Procurement	205	0.67							154	0.50
Harvesting	4,366	14.24							3,280	10.70
Chipping	824	2.68							619	2.02
Mining			1,088	3.55	4,022	13.12	4,218	13.76	1,115	3.64
Cleaning					843	2.75			234	0.76
Transportation	718	2.34	5,800	18.92	2,880	9.39	2,872	9.37	1,265	4.13
Plant	6,230	20.32	6,500	21.20	6,500	21.20	6,500	21.20	6,650	21.70
Emission control	690	2.25	970	3.16	970	3.16	2,850	9.30	970	3.16
Operation and maintenance	710	2.32	710	2.32	710	2.32	710	2.32	750	2.45
Total	13,743	44.82	15,068	49.15	15,925	51.94	17,150	55.94	15,037	49.06

TABLE 40. SENSITIVITY OF POWER-GENERATION COSTS TO FUEL COSTS
50 MW POWER PLANT, CENTRAL VERMONT - 1980

	Mills per kwh			Percent Change In Generation Cost with Indicated Change in Fuel Costs	
	Cost Projected to 1980	Fuel Cost			
		Increased 25%	Decreased 25%	25% Increase	25% Decrease
Green Wood					
Fuel	17.59	21.99	13.19		
Generation	44.82	49.22	40.42	+ 9.8	- 9.8
Low-Sulfur Coal					
Fuel	3.55	4.44	2.66		
Generation	49.15	50.04	48.26	+ 1.8	- 1.8
Cleaned Coal					
Fuel	15.87	19.84	11.90		
Generation	51.94	55.91	47.97	+ 7.6	- 7.6
High-Sulfur Coal with Stack-Gas Cleaning					
Fuel	13.76	17.20	10.32		
Generation	55.94	59.38	52.50	+ 6.2	- 6.2
75% Green Wood, 25% Cleaned Coal					
Fuel	17.62	22.06	13.22		
Generation	49.06	53.48	44.60	+ 9.0	- 9.0

TABLE 41. SENSITIVITY OF POWER-GENERATION COSTS TO TRANSPORTATION COSTS 50 MW POWER PLANT, CENTRAL VERMONT - 1980

	Mills per kwh			Percent Change in Generation Cost with Indicated Change in Transportation Cost	
	Cost Projected to 1980	Transportation Cost Increased 25%	Transportation Cost Decreased 25%	25% Increase	25% Decrease
Green Wood					
Transportation	2.34	2.93	1.76		
Generation	44.82	45.41	44.23	+1.3	-1.3
Low-Sulfur Coal					
Transportation	18.92	23.65	14.19		
Generation	49.15	53.88	44.42	+9.6	-9.6
Cleaned Coal					
Transportation	9.39	11.74	7.04		
Generation	51.94	54.29	49.59	+4.5	-4.5
High-Sulfur Coal with Stack-Gas Cleaning					
Transportation	9.37	11.71	7.03		
Generation	55.94	58.28	53.60	+4.2	-4.2
75% Green Wood, 25% Cleaned Coal					
Transportation	4.13	5.16	3.10		
Generation	49.06	50.09	48.03	+2.1	-2.1

is most sensitive. When fuel costs and transportation costs are combined, the changes in power generation costs tend to equalize for the five types of plants, but costs at the plant using cleaned coal are the most sensitive and those at the plant burning high-sulfur coal are least sensitive.

Effect of Changing Costs of Pollution Control

The calculated impacts of 25 percent increases and 25 percent decreases in costs of pollution control on the costs of power generation are shown in Table 42. Generation costs at the plant burning high-sulfur coal with stack gas cleaning are more sensitive to changes in pollution control costs than are those at any of the other plants.

Effect of Changing Plant Size

The calculated impacts of 25 percent increases and 25 percent decreases in plant size on the costs of power generation are shown in Table 43. Note that increased costs of generation are associated with decreased plant size, and vice versa. Generation costs at the plant burning high-sulfur coal are slightly more sensitive to plant size than are generation costs at other types of plants.

TABLE 42. SENSITIVITY OF POWER-GENERATION COSTS TO POLLUTION-CONTROL COSTS
50 MW Power Plant, Central Vermont - 1980

	Mills per kwh			Percent Change in Generation Cost with Indicated Change In Emission-Control Cost	
	Cost Projected to 1980	Pollution-Control Cost			
		Increased 25%	Decreased 25%	25% Increase	25% Decrease
Green Wood					
Emission Control	2.25	2.81	1.69		
Generation	44.82	45.38	44.26	+1.2	-1.2
Low-Sulfur Coal					
Emission Control	3.16	3.95	2.37		
Generation	49.15	49.94	48.36	+1.6	-1.6
Cleaned Coal					
Emission Control	3.16	3.95	2.37		
Generation	51.94	52.73	51.15	+1.5	-1.5
High-Sulfur Coal with Stack-Gas Cleaning					
Emission Control	9.30	11.63	6.98		
Generation	55.94	58.27	53.62	+4.2	-4.2
75% Green Wood, 25% Cleaned Coal					
Emission control	3.16	3.95	2.37		
Generation	49.06	40.85	48.27	+1.6	-1.6

TABLE 43. SENSITIVITY OF POWER-GENERATION COSTS TO PLANT SIZE
50 MW Power Plant, Central Vermont - 1980

	Mills per kwh(a)			Percent Change in Generation Cost with Indicated Change in Plant Size	
	Cost Projected to 1980	Plant Cost			
		Size Increased 25%	Size Decreased 25%	25% Increase	25% Decrease
Green Wood					
Plant	22.57	20.64	25.33		
Generation	44.82	42.89	47.58	-4.3	+6.2
Low-Sulfur Coal					
Plant	23.45	21.45	26.31		
Generation	49.15	47.15	52.01	-4.1	+5.8
Cleaned Coal					
Plant	23.45	21.45	26.31		
Generation	51.94	49.94	54.80	-3.9	+5.5
High-Sulfur Coal with Stack-Gas Cleaning					
Plant	30.50	27.89	34.22		
Generation	55.94	53.33	59.66	-4.7	+6.6
75% Green Wood, 25% Cleaned Coal					
Plant	23.95	21.89	26.88		
Generation	49.06	47.00	51.99	-4.2	+6.0

(a) Plant costs include both the basic plant and emission control facilities, which will change in size with the plant.

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ENVIRONMENTAL-ECOLOGICAL IMPACTS OF WOOD FUEL USE

The objectives of this effort are to review and evaluate existing information on the environmental impacts of the forest management practices which are proposed for the procurement of wood-derived fuels in Vermont. Environmental effects considered are: (1) silvicultural practices: nutrient budget; (2) stream water quality impacts of tree harvesting; (3) soil erosion; (4) effects on wildlife; and (5) aesthetics. Recommendations for (a) forest management practices needed to minimize environmental impacts, and (b) additional studies which are needed to correlate wood procurement practices with environmental impacts, are presented.

Silvicultural Practices: Nutrient Budget

The current interest in managing forest residuals has raised a number of questions pertaining to the stability and longivity of American forests. A review of the literature on environmental impacts of forest management practices related to soil nutrient removal and its effects on forest productivity indicate that definitive, comparable data are not available. No studies of this kind have been published about the forests of Vermont.

Three aspects of silvicultural practices - soil nutrient removal are discussed: (1) nutrient removal; (2) nutrient inputs; and (3) rotation periods.

Nutrient Removal

Forests remove definable amounts of nutrient materials from the soil each year. The rate of uptake depends on many factors, i.e., stocking, species of tree, age of stand, soil nutrient availability, available moisture, etc. For example, Jorgensen et al(1)* indicate that a 16-year old pine plantation, in North Carolina, removed 321 Kg/ha of nitrogen, 48 Kg/ha of phosphorous and 226 Kg/ha of potassium (Table 44). These trees were growing at a stocking rate of 2,243 stems per hectare with a site index of 68 at age 25.

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* References for this Section are given on page 202

TABLE 44. DISTRIBUTION OF TREE BIOMASS AND NUTRIENTS IN A 16-YEAR-OLD LOBLOLLY PINE PLANTATION IN THE NORTH CAROLINA PIEDMONT

Component	T/ha Biomass	Kg/ha N	Kg/ha P(a)	Kg/ha K(a)
Trees				
Needles	8.0	82	10	48
Branches	23.2	60	6	28
Stemwood	109.6	79	11	65
Stem Bark	15.2	36	4	24
Root Total	36.3	64	17	61
Total Tree	192.3	321	48	226
Forest Floor	-	307	30	28
Mineral Soil, 0-70 cm	-	1,753	371	404
Site Total		2,381	449	658

(a) Total in vegetation and forest floor and extractable in mineral soil

Source (1)

As shown in Table 45, a wide variation exists in the amounts of nutrients contained in the above ground portions of growing trees. Rennie's(2) data represent growth on nutrient-poor soils; his recommendation was to leave brush and stembark on the forest floor so that a minimum of nutrients would be removed from the site. Morrison and Foster(3) analyzed the vegetation growing on two soil types: till and sand. They attribute the increased nutrient concentrations, in vegetation from the till soils, to increased soil moisture, increased soil depth, and a larger percentage of silts and clays in the till soil. Deriegneau and Denaeyer-DeSmet(4) attribute the higher nutrient uptake associated with the mature _Quercus_ _Fraxinus_ forest to available nutrient concentrations in the soil.

Several authors have related nutrient removal to harvest technique. Malkonen(5) compared whole tree harvesting, including roots, to normal logging procedures in Findand (Table 46). His data indicate almost a threefold increase in nitrogen removal due to whole tree harvesting. The data also indicate the differences due to species and site.

Jorgensen et al (1) measured the effect of harvest method on biomass and nutrients from a 16-year old loblolly pine plantation in the North Carolina Piedmont (Table 47). These data are most important in that a management decision about market/residue-manipulation relationships can be made. The authors state:

> "At about 16 years of age, highly productive plantations can be clearcut or thinned for pulpwood. In a 16-year old stand, removal of needles, bark, branches, stems, and large roots would yield 185 metric tons/ha of biomass. This material would contain about 80 to 90 percent of the nutrients in the tree biomass, 12 percent of the total nitrogen, 8 percent of the extractable phosphorous, and 31 percent of the extractable potassium on the entire site. A much less drastic harvest alternative now generally employed, removing only the stemwood and bark to an 8-cm top, would yield 116 metric tons/ha. This form of harvest takes away only about one-third as much nutrients as total-tree harvest, but yields two-thirds as much biomass. Furthermore, the biomass left

TABLE 45. NUTRIENT REMOVAL - ABOVE GROUND TREES ONLY

Species	N	Ca	K	P	Mg	Source
			kg/ha(a) (100 yr rotation)			
Pines	-	283	138	30	-	Rennie (2)
Other Conifers	-	676	375	70	-	Rennie (2)
Deciduous Hardwoods	-	1,283	320	70	-	Rennie (2)
			kg/ha/yr(a)			
Jack Pine Stand (till)	24	18	12	2	3	Morrison and Foster (3)
Jack Pine Stand (sand)	16	12	11	1	2	Morrison and Foster (3)
Fagus sylvatica	10	13	4	2	-	Duvigneaud and Denaeyer-De Smet (b) (4)
Pinus sylvestris	10	10	2	1	-	Duvigneaud and Denaeyer-De Smet (4)
Quercus Fraxinus	44	42	-	4	5	Duvigneaud and Denaeyer-De Smet (4)
Mixed Oak	30	75	16	2.2	4.4	Duvigneaud and Denaeyer-De Smet (4)
Querceto-fraxinerum	44	42	21	4	5	Duvigneaud and Denaeyer-De Smet (4)
Quercetum mixtum	30	74	16	2.2	6	Duvigneaud and Denaeyer-De Smet (4)
Querecto-aegopodietum	56	20	27	3	1	Duvigneaud and Denaeyer-De Smet (4)
Querecto-aegopodietum	33	16	23	4	3	Duvigneaud and Denaeyer-De Smet (4)
Fagetum	16	26	8.8	1.2	2.5	Duvigneaud and Denaeyer-De Smet (4)
Fagetum on diorite	-	49	4.5	6.1	5.3	Duvigneaud and Denaeyer-De Smet (4)
Fagetum on granite	-	23.8	2.5	2.8	2.5	Duvigneaud and Denaeyer-De Smet (4)
Betuletum verrucosae	8	10	3	0.5	0.9	Duvigneaud and Denaeyer-De Smet (4)
Picea Forest	20.6	22.5	6.7	1.8	2.2	Duvigneaud and Denaeyer-De Smet (4)

(a) kg/ha = 0.89218 lb/acre

(b) Literature reviewed by these authors.

TABLE 46. COMPARISON OF TWO HARVESTING TECHNIQUES IN FINLAND

Technique	kg/ha			
	N	Ca	K	P
Pine Forest				
Timber Cut	58	73	38	5.3
Whole Tree Harvest (including root)	148	115	80	15.0
Spruce Forest				
Timber Cut	95	184	47	8.4
Whole Tree Harvest (including root)	372	409	161	40.6

Source (5)

TABLE 47. EFFECT OF HARVEST METHOD ON BIOMASS AND NUTRIENTS FROM A 16-YEAR-OLD LOBLOLLY PINE PLANTATION

Harvest Method	Tree Biomass		Nutrients in Biomass						Nutrients in biomass expressed as a percentage of nutrients on site		
			Weight			Percentage					
	Weight	Percentage	N	P	K	N	P	K	N	P[a]	K[a]
	T/ha		kg/ha								
Debarked pulpwood to 8-cm top	102	53	74	13	61	23	27	27	3	3	9
Pulpwood to 8-cm top	116	60	104	14	80	32	29	35	4	3	12
Complete aerial	156	81	254	30	165	79	63	73	11	7	25
Complete aerial + roots 4-cm and larger	185	96	282	37	202	88	77	89	12	8	31
Total biomass aerial and below ground	192	100	321	48	226	100	100	100	13	11	34

(a) Total nitrogen and forest floor and extractable in soil

Source (1)

is mostly of low quality for manufacturing, and costs for manufacturing and waste disposal may exceed the return released from harvest. Removing only debarked pulpwood takes about 20 percent less N, P, and K from the site than a normal pulpwood harvest, and reduces the weight yield by only 10 percent.

Patric and Smith(6) calculated nutrient losses from several West Virginia experimental watersheds under current silvicultural practices (Table 48). The stands were uneven-aged, consisting of old second growth oaks, maples, yellow poplar, black cherry and beech; residuals from a heavy cutting in 1905 were present.(6) These data indicate that repeated light cuts tend to cause greater annual nutrient drain than does a single cut per rotation.(6)

Nutrient Input

Nutrient input to a forest system occurs primarily by (1) mineralization of the solum and weathering of secondary materials in the soil; (2) atmospheric inputs in the form of particulates, and dissolved materials in precipitation; and (3) from organic inputs from the vegetation itself. These inputs to the forest system, under normal circumstances, are usually sufficient to balance losses.(1) In most soils, natural weathering of soil materials along with low levels of nitrogen fixation and atmospheric contributions seem ample to replace nutrient removals(7).

Nutrient additions through fertilization or nitrogen-fixing plants can establish high productivity rates in the forest ecosystem, especially when deficiency conditions exist.(8) More research is needed to determine how widespread deficiencies may be, as well as to answer questions of how much, when, and where fertilizer is to be applied.(9) These authors made an extensive survey of investigators currently doing forest fertilization research in northeastern United States hardwoods.

Forest fertilization methods and quantities have been analyzed by Groman(10) and recommendations are given. Few studies indicate no

TABLE 48. ESTIMATED NUTRIENT LOSSES ACCOMPANYING SILVICULTURAL PRACTICES ROUTINELY APPLIED ON THE FERNOW EXPERIMENTAL FOREST, PARSONS, W. VA.

	Cycle[a] (yr.)	kg/ha		
		Harvested Biomass	Nutrients[b] removed from soil[c]	
			per cycle	per year
Intensive selection (selected trees over 12.5 cm dbh)	5	10,323	98	20
Extension selection (selected trees over 27.5 cm dbh)	10	22,237	180	18
Diameter limit (all salable trees over 43 cm dbh)	20	25,221	236	12
Commercial clearcutting (all salable trees over 12.5 cm dbh)	75	51,030	473	6
Liquidation cutting (all salable trees branches and culls)	75	94,295	892	12

(a) Frequency of recutting

(b) N, P, K, Ca, Mg

(c) Computed as 88% of the harvested biomass as wood, 12% as bark; applying nutrient content to biomass ratios for stemwood and bark (from Duvigneaud and Denaeyer-De Smet). (4)

Source (6)

substantial or long-term detrimental effects to the environment from forest fertilization. Some examples of application rates are:[(10)]

Sweden	132 kg/ha	N
Pacific Northwest	150-200 kg/ha	N
Southern Pines	90-112 kg/ha	P_2O_5

Application of fertilizers to forests is a recent management practice. It started in the 1950's and by 1970 about 5 million acres in the world were fertilized; it is projected that by 1980 the figure would be 40 million acres.[(11)]

Available data for long-term results of application of N or combinations of N, P, and K are not available. However, Stone[(12)] attributes the reasons for fertilizer application to either acceleration of already favorable growth rates on productive sites, or to allow reasonable normal growth on soils either naturally deficient or depleted by an earlier cycle of exploitive agriculture. Forest fertilization does offer a management tool to offset any long-term effect of nutrient removal due to harvesting practice.

Rotation Period

Man has been removing parts of forests, or complete forests for centuries. Sometimes the results were disastrous (due primarily to erosion) but in situations where soil conditions were favorable, the forest ecosystems recovered. Stone[(12)] reviewed the literature and concludes that increased nutrient removal is likely to be a minor problem from complete tree utilization. There is increased nutrient loss, however, in such practices as

Shorter rotations
Faster growing varieties
Closeness of tree plantings.

Boyle et al[(13)] calculated a gross nutrient budget for a 40-year old aspen-mixed hardwood second growth forest in Wisconsin (Table 49). The authors calculate that nutrient inputs would more than sustain nutrient removal due to whole tree harvesting for at least nine 30-year rotations. The only potential limiting factor was calcium; this estimate was based on

TABLE 49. GROSS NUTRIENT BUDGET FOR THE HARVEST SITE

Item	N $NH_4 + NO_3 - N$	P	K	Ca
		(- Extractable)		
		lb/A		
Soil reserves (top 6 inches) at time of harvest[(a)]	24	102	115	586
Inputs expected during next 30 years from:				
Precipitation	150	9	67	107
Mineralization & weathering	486	27	107	214
Net Inputs	636	36	174	321
Outputs in whole tree harvest at age 30	172	24	116	382
Input/Output index[(b)]	3.7	1.5	1.5	0.8

(a) These minimal reserves are supplemented by available nutrients in soil horizons below 6 inches which are penetrated by roots.

(b) An index number greater than 1 indicates inputs during the 30-year rotation are more than adequate to balance harvest outputs. A value less than 1 indicates a potential limiting supply when soil reserves are exhausted.

Source: Reference 13.

Ca content of the top 6 inches of soil. However, increased nutrient removal due to increased runoff was not calculated.

Wells et al (14), as cited by Patrick and Smith(6), calculated the replenishment of soil nutrients in a North Carolina hardwood forest (Table 50). Total annual input of N, P, K, Ca, and Mg equals 235.65 Kg/ha. Patric and Smith(6) calculated a maximum annual removal rate of N, P, K, Ca, and Mg of 20 Kg/ha (Table 47). One could conclude that a net annual increase of 215.65 Kg/ha of N, P, K, Ca, and Mg occurs under intensive selection harvesting. However, losses due to erosion and runoff were not included in the calculations.

Conclusions

1. Forests remove definable amounts of nutrients from the soil. The rate of removal is dependent on: (1) species; (2) stocking; (3) age of the stand; (4) available moisture; and (5) soil nutrient availability.
2. The amount of nutrients removed from a site, due to silvicultural practices, varies with the practice and the variables mentioned in conclusion 1.
3. The effect of nutrient removal, by harvest, is not known at this time. Available data are site specific and are not amenable to comparisons or projections.
4. Nutrient inputs to forests are variable and are not yet fully quantifiable.
5. Forest fertilization practices could serve as a source of nutrients. However, fertilization suggests good forest management. Due to the land ownership patterns in Vermont, fertilization may not be feasible on private lands; fertilization would be feasible on state lands.

TABLE 50. REPLENISHMENT OF SOIL NUTRIENTS IN A NORTH CAROLINA HARDWOOD FOREST

	Nutrients (kg/ha)				
Source	N	P	K	Ca	Mg
Rainfall	3.53	0.28	0.88	3.42	0.72
Canopy Drip	4.86	0.61	17.48	12.47	3.75
Stemflow	0.23	0.01	0.65	2.02	0.24
Litter	45.98	3.26	14.16	94.99	18.11
Annual Input to Soil	54.60	4.16	33.17	120.90	22.82

Source (14)

Stream Water Quality Impacts Of Timber Harvesting

The State of Vermont has the good fortune to have within its borders many thousands of acres of relatively undisturbed forestland and semi-wilderness areas. As watersheds, these areas are characterized by consistently high stream water quality. With the proposed activity of harvesting forests for energy production, the question arises as to what effects this practice will have on water quality in the associated streams.

The traditional parameter of quality in forest streams is turbidity. Only in the last decade has it been recognized that this criterion is an insufficient measure of the quality of forest streams, because the chemical composition of identically turbid or nonturbid waters may vary widely. Therefore, a number of different water quality parameters must be assessed in an evaluation of these streams and of the impacts of timber harvesting practices on stream quality. Impacts of timber harvesting on water quality values are reviewed as follows:

- Stream flow
- Water temperature
- Turbidity
- Nutrients and other ions
- Other parameters.

For clarification, the data are presented in three sections: (1) impacts and mitigating measures; (2) policy implications in Vermont; and (3) conclusions.

Impacts and Mitigating Measures

In general, there are at least three sets of variables influencing how stream water quality will be impacted by timber harvesting. The first of these is the nature of the forested area before harvest - the composition of the soil, the depth of the humus, the extent of forest cover in the area, the species of trees affected, etc. Secondly, the original physical and

and chemical composition of the associated streams will influence the final result. The third set of factors centers on the harvest operation itself - whether clearcutting or an alternate method is employed, whether a buffer strip of trees is left next to the stream, and whether the slash is left behind or somehow destroyed.

The studies conducted on this particular topic have not always been careful to note all of these variables. Moreover, there is one relatively well known study in which an additional factor was incorporated within the experimental design. On one tract within New Hampshire's Hubbard Brook Experimental Forest, the trees and vegetation were killed and left in place, and regrowth was prevented for 2 years by application of an herbicide. Because of inconsistencies from one study to another, the results are not always directly comparable. In trying to predict the outcome within a given Vermont forest and its watershed, one should be cognizant of such pitfalls and assimilate as much information as possible about management decision.

Stream Flow. In an undisturbed forested area, the capacity of the soil to accept rainwater is very high, usually higher than the capacity of major intensity storms to deliver water to these areas. Typically, heavy cutting of the forest will not affect this property of the soil unless the soil itself is disturbed. This does not mean, however, that the quantity of runoff is unaffected when the canopy is removed. For example, see Figure 30a.

In the Hubbard Brook study, it was shown that annual runoff from the area, which was deforested but which retained an undisturbed soil layer, increased by 39 percent the first year and 28 percent the second year over values that were based on a control area. June and September runoff values were 414 percent and 380 percent higher than for controls. Likens et al(15) postulate that such results are a function of the reduced canopy during these months. This conclusion is accepted by Stone.(12) According to Stone, destruction of leaves and their transpiring surface area reduces the level of water intake necessary

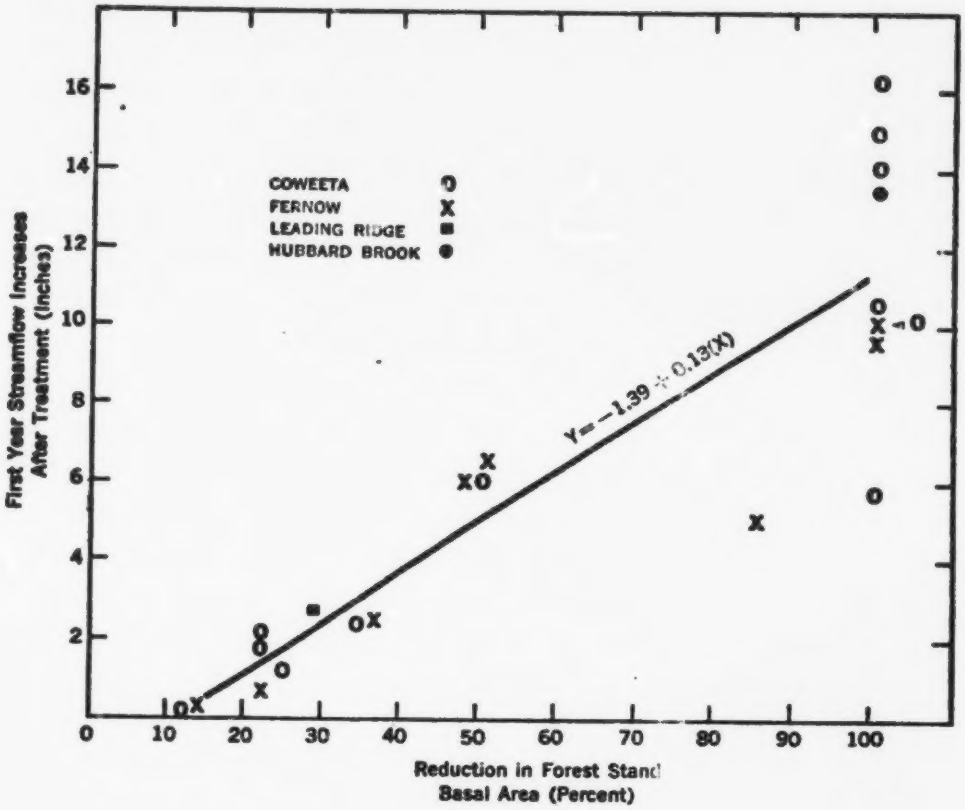

FIGURE 30a. INCREASED STREAMFLOW IN THE FIRST YEAR OF CUTTING

Source: Reference 12.

by vegetative roots. At the extreme, an absence of living vegetation in the area which previously had been forested, such as Hubbard Brook, removes the requirement for roots to take up any water at all. If the water seepage through the soil is too slow to accommodate this increased burden, then runoff and stream flow will also rise. On the other hand, reestablishment of the foliage canopy will accompany increasing water uptake by roots and a reduction in stream flow.(12) This appears to occur in a systematic and reoccurring pattern. In one experiment by Hibbert(16), as cited by Stone, a clearcut forest in North Carolina displayed the predicted increase in water yield, followed by a gradual abatement over 23 years as the forest regrew; a subsequent clearcut after that period of time then reproduced virtually an identical increase in water yield.

Regardless of harvesting status, the period of greatest stream flow discharge from a Vermont forest is likely to be in late March and April, when snowmelt is fastest. Likens et al(15) have documented this result in neighboring New Hampshire. Snowmelt took place a few days in advance in the denuded forest; the watershed discharge in 1968 was almost 30 percent greater in volume at its early spring peak than in the continuously forested control area. The implications of this finding are that any potential flood situation during this time of year might be increased by the presence of widespread cleared forestland.

Water Temperature. The impacts of timber harvesting on ambient stream temperatures within a watershed appear to be relatively well understood. Removal of the forest cover permits direct solar radiation into the stream. Brown(17) reports that the solar heat load was increased by six times after the shading overstory had been removed. The results are twofold: not only will there be higher water temperatures, but the daily fluctuation between maximum and minimum will be greater as well. Such changes appear to be a function of solar radiation directly into the stream, not increased air or soil temperatures.

The degree of warming of a stream is not as well understood, although several contributory factors have been identified. Levero and Rothacher(18) have found that temperature increases in streams, after complete exposure to the sun, ranged up to as much as 8.3 degrees centigrade. The variation in response by individual streams seems to be accounted for by the length of channel exposed, the original width of the stream, the volume of water and its initial temperature, and the amount of canopy removed.

Stream water temperatures in New Hampshire's Hubbard Brook area proved to be higher both in summer and in winter within the cleared area than in the control area.(15) Annual variation in the deforested watershed was between 18 to 20 degrees C whereas in the control area it ranged only about 16 degrees C. Daily fluctuations in summer were also greater in the experimental area; mean hourly stream temperature, during 1 day in summer, went from approximately 18 degrees C to about 22 degrees C , while in the control watershed, temperature remained fairly constant at 16 degrees C.

Experiments by Brown et al(19), in the Steamboat Creek drainage of Oregon's Cascade Mountains, have shown that the segment length exposed to solar radiation is a very important factor in determining the degree of temperature increase. On a very small stream, a 10-foot cut along the stream produced a 1.1 degree C rise in temperature, a 30-foot cut resulted in a 2.2 degree C increase, and a 150-foot cleared stretch along another very small stream induced the temperature in that stream to rise by 7.2 degrees C.

The fact that length of stream exposed to the sun is not the only factor involved is demonstrated on another wider stream in the Steamboat Creek area. A clearcut which exposed 1,100 feet of stream produced a rise of only 2.2 degrees C , from 22.2 degrees C to 24.4 degrees C. The two additional factors involved here were the relatively high initial 22.2 degrees C reading, which was brought about by other clearcuts upstream of the one studied, and the greater width of the stream segment.

One study conducted by Escher and Larmoyeux(20), in West Virginia's Fernow Experimental Forest, reported that clearcutting in a given area resulted in temperatures greater than those which can be tolerated by rainbow, brook, and brown trout. Water temperatures in excess of 24 degrees C (75 degrees F) were noted a number of times.

Many studies have pointed out that stream temperature increases, after a clearcut, can be controlled and even prevented. Because of the importance of shade, a buffer strip left adjacent to the stream has been shown very effective in maintaining stream temperatures through a clearcut area. In the Steamboat Creek area, a narrow strip of trees and brush along a 1,680-foot exposure of stream prevented temperatures along that segment from rising more than 1 degree F - from an initial 14.4 degrees C to a downstream reading of 15 degrees C. On another stream where the upstream reading was 24.4 degrees C , there was no increase in temperature when a buffer was left to protect the stream. Similar results have been reported in a Southeastern forest when a thin strip of vegetation had been left along the stream channel.

In West Virginia's Fernow Experimental Forest, a 10 to 20 meter wide protection strip was left on both sides of the channel along a clearcut stretch approximately 730 meters long. Not only were stream temperatures virtually unchanged along this length, but a comparison of readings with those taken for several years before the cut indicated no rise. Moreover, the increase in stream flow caused by the clearcut had an additional result of extending the stream almost 200 meters upchannel into the clearcut area; the presence of direct solar heating of this water did not produce a downstream temperature rise.

Turbidity. The major cause of turbidity increases in a forested watershed is not the harvesting practice but the building of logging roads and skid trails. The degree of disturbance is related to the slope of the terrain, the stability and erosiveness of the soils, and the distance of disturbance activity from the stream channel. Most observers are of the opinion that slight marginal improvements in planning and construction of logging roads can prevent most of the increased turbidity impairment to water quality.

In the Hubbard Brook experiment(15), where the vegetation was left in place after the tract was cut over and herbicided, no increases in water turbidity were displayed. If anything, the values seemed somewhat lower than in undisturbed watersheds.

Results from the Fernow Experimental Forest are also important. According to Aubertin and Patric(21), most of the increase in turbidity was related to storm activity. During nonstorm periods, turbidity levels were generally low throughout the area, even in streams adjacent to logging roads. Despite precautionary measures taken to lessen road-related turbidity, highest levels were found in stormy periods where logging roads were adjacent to protective buffers. During one particularly intense storm, erosion control structures were damaged next to a heavily used road; at the point that the resultant runoff mingled with a stream, turbidity was at 550 Jackson turbidity units, whereas several feet upstream of the mixing zone it was at only 25 Jackson turbidity units.

A study by Kochendeefer and Aubertin(22) in the West Virginia forest demonstrated that a carefully planned, constructed, and maintained road system can keep turbidity increases to a very minor level. In contrast, a nearby commercial clearcut in the same forest produced a major rise in this parameter. The absence of logging road restrictions in the latter tract was deemed the most important causative factor.

The United States Forest Service has been instrumental in developing guidelines to reduce damage to watersheds caused by erosion.(23) These guidelines cover road locations and design, construction of permanent roads, drainage control, and road maintenance. They should be consulted during harvesting activities so that such impacts can be minimized.

Nutrients and Other Ions. According to Likens and Bormann(24), it is the input of dissolved nutrients to a freshwater ecosystem which determines that system's ultimate trophic status. In general, the nutrient cycle within a forest ecosystem is a closed loop, and there is little loss of nutrients into drainage waters. Likens and Bormann(25) have shown, in fact, that an undisturbed forest ecosystem within the Hubbard Brook area displayed an annual net gain in nitrogen and phosphorus and a near balance in potassium, despite the continuous mobility of these nutrients in the ecosystem.

The degree of nutrient loss from a forested area after it has been clearcut is important for two reasons. For one thing, a heavy loss would contribute to an adverse water quality situation by resulting in an accelerated rate of eutrophication. In addition, productivity of the forest site might also be impaired.

The most dramatic example of nutrient losses following a clearcut, though not all nutrients displayed the same pattern, took place in the Hubbard Brook tract of New Hampshire. In this case, the felled vegetation was left in place, the soil remained relatively undisturbed owing to the lack of road construction and timber removal, and the area was treated with herbicides for the three ensuing summers to prevent regrowth. The undisturbed watershed showed a very low ammonium concentration, and there was virtually no change after deforestation. These data are explained by the fact that growing vegetation in the undisturbed forest may use the ammonium ions directly, thus depleting their presence in stream flow, but when growing vegetation is absent, the process of biological nitrification converts the ammonium ions to nitrite and then to nitrate ions. In both forest situations, therefore, presence of the ammonium ions in the associated streams is minimal.

The nitrate ion, in contrast, increased markedly in the tract's watershed after deforestation. Low levels of nitrate were present in the drainage water of the undisturbed ecosystem, reflecting both the efficiency of the conversion process from ammonium to nitrate as well as the usage of these nitrates by the vegetation. After deforestation, ammonium was reduced to nitrates by the vegetative root system. The result was continuous leaching of nitrates through the soil and a significant rise in the concentration draining from the watershed. Prior to the cutting, the average weighted value of the nitrate concentration was 0.9 mg/liter; 2 years after cutting it had increased to 53 mg/liter; the maximum monthly concentration after deforestation was 82 mg/liter.

A related study by Pierce et al(26) examined the effects of timber harvesting by commercial clearcut methods. On these tracts, also located in the Hubbard Brook area, shrubs and saplings were left standing, and herbicides were not applied to prevent regrowth. Again, concentrations of nitrates rose significantly, but not nearly as much as in the water draining the experimental tract. Maximum nitrate concentration in these areas was 28 mg/liter, as compared with 82 mg/liter from the experimental area. Total losses of nitrate-nitrogen were also substantially less over the 2 years following the cut.

Studies from other Eastern forest areas do not corroborate the results from New Hampshire. In West Virginia's Fernow Experimental Forest, Aubertin and Patric(21) observed the results after a tract had been commercially clearcut. Nitrate-nitrogen levels increased only slightly over a control watershed during the ensuing growing season; a somewhat larger increase took place afterwards in the dormant season. Overall nitrogen losses, however, were relatively small. The authors postulate that the losses which did occur resulted from a buildup of nitrogen in the soil during the growing season, which was leached during heavy dormant season rainfall. Heavy nutrient shifts did not occur, though, because timber was not left to decay on the forest floor, and regrowth of the tract was both rapid and luxuriant.

Nutrient losses were also studied by Lynch et al(27) in Pennsylvania. After a three-phase clearcut was undertaken, herbicides were applied to the tract to prevent regrowth of woody sprouts. A large invasion of herbaceous vegetation took place, however, and much of the available nitrogen was thus utilized. Significantly higher levels of nitrate-nitrogen were not observed on the experimental tract.

Other nutrients displayed patterns similar to those of ammonium and nitrate, and results differed depending on the experimental method. In the Hubbard Brook area, calcium, magnesium, potassium, and sodium cations all increased in average stream water concentrations following deforestation.

In a comparison of clearcut and control areas of Fernow, however, these four cations demonstrated minor increases in nutrient loss during the growing season and similar values in the dormant seasons. Discrepancies between the two experiments are thought to be based on the absence of herbicide treatment in Fernow. Separate studies by Johnson and Swank(28), and Douglas and Swank(29) in North Carolina's Coweeta National Forest verify the results from West Virginia, with the predictable exception that calcium concentrations increased substantially in the watershed after a clearcut area received lime applications.

The sulfate ion is the only additional parameter studied both at Hubbard Brook and in the Fernow Experimental Forest. Values varied, although, in both cases ; the experimental tracts seemed to portray lower sulfate concentrations in their respective watersheds. These decreases, moreover, came about only after a several month lag. Complicated mechanisms of precipitation chemistry and internal biological activity of the ecosystem underlie the reasons for such changes(15).

The impact of timber harvesting on phosphate concentrations was examined in the Fernow forest, where a temporary increase in concentration was found adjacent to the clearcut area. Aubertin and Patric(21) do not postulate any reasoning for this temporarily greater loss from the cut area, but the same factors appear to be at work here as for nitrates. Phosphates were not being taken up into root systems directly after the clearcut, but as the vegetation began to regrow, this nutrient came more and more into demand, and thus the increased losses into the water were only short lived.

Other chemicals were studied in one of the two experiments. Chloride concentrations increased in Hubbard Brook, mostly as a result of the chlorine component of the herbicides. Aluminum and dissolved silica also increased in Hubbard Brook; a decrease in the pH of the stream water raised the solubility of both of these chemicals, and thus their concentrations rose. Another impact of this decrease in stream water pH centered on a lowering of bicarbonate ion concentration to near zero. Copper, zinc, and iron levels were all measured in the Fernow tracts, and none seemed to be affected by the harvest.

More recent studies at Hubbard Brook are attempting to pinpoint methods for abating the increases in concentrations of nitrates, potassium, and calcium. As reported by Hornbeck et al(30), a partial clearcutting method known as strip cutting was applied in one tract. In this instance, approximately 50 east-west strips were laid out on the tract, and every third strip was cut during that year. The two sets of remaining strips would be cut similarly in 2-year intervals. Results from this experiment showed that nutrient losses from the forest could be mitigated significantly, though losses were still substantial. Efforts are continuing in Hubbard Brook to discover feasible methods for improvements in reducing nutrient losses.

Other Parameters. The concentration of hydrogen ions in stream water is affected by nutrient and other chemical release into the water. Because such losses were relatively small in Fernow, the pH was not changed. In Hubbard Brook, on the other hand, the weighted average pH decreased from 5.1 to 4.3 over the space of 2 years. This change, as has been mentioned above, resulted in rising solubility levels for chloride and dissolved silica, which thereupon increased in concentration.

Total dissolved solid content in the Fernow watershed did not change as a result of the timber harvest activity. The related parameter of electrical conductivity was studied at Hubbard Brook. In the undisturbed watershed, electrical conductivity averaged about 20 micromos/cm^2 at 25 degrees C , and changed very little either daily or seasonally. At the same time, conductivity in the denuded watershed was relatively variable and ranged from 65 to 160 micromhos/cm^2 at 25 degrees C. Timing and duration of rainfall as well as other factors appeared to affect this parameter.

Policy Implications in Vermont

The effects of timber harvesting practices on water quality is a subject which falls within the purview of at least two major categories of environmental concern:

- Land use
- Water pollution.

The implications of this activity on environmental policy and law in the State of Vermont will be discussed in the above order.

Land Use. Approaches to land use controls are both general and specific in Vermont. The state's 1970 land use law, Act 250, is a general outline of concern for these issues, and it contains certain action-forcing mechanisms. More specific to the activity of timber harvesting are certain practices and guidelines issued by the Vermont Department of Forests and Parks.

Act 250, as originally adopted in 1970, created an environmental board and district environmental commission to regulate land use. The state board was directed to develop state land capability and land use plans, as well as to set up a permit system to carry out the plans. The "Capability and Development Plan" was thereupon prepared, and, in 1973, the state legislature passed amendments to Act 250 to adopt the plan as state policy and establish specific criteria for the issuance of permits. As for the land use plan, it has been prepared, but the legislature has not yet acted to adopt it formally.

The 1973 amendments to Act 250 place under state permitting authority virtually all land development activities of significance. In brief, anyone designing to "develop" land must procuce a 250 permit. To determine if timber harvesting practices would require a permit, one should look for the applicable definitions of "development", as expressed in the adopted amendments. The relevant provisions are that "development" encompasses the following:

- Construction for any purpose above 2,500 feet in elevation
- Quarrying and earth removal, with the stated exemption of any construction for farming, logging, and forestry purposes below 2,500 feet in elevation.

It is possible, therefore, that the construction of logging roads and other necessary facilities above 2,500 feet in elevation would create a requirement that the developer secure a 250 permit.

In cases where such a permit must be obtained, there are environmental standards which must be addressed by the potential permittee. In specific, a timber harvester would have to demonstrate that his development:

- Does not interfere with headwaters within a watershed
- Contains proper waste disposal means and facilities
- Utilizes the best available technology to preserve stream water quality
- Does not significantly interfere with flood waters
- Does not interfere with the natural condition of any stream
- Is located on the shoreline of a body of water only out of necessity and in conformance with shoreland zoning requirements
- Does not unreasonably burden an existing water supply
- Does not unreasonably erode soil or reduce the water holding capacity of the soil
- Does not adversely affect aesthetic, historic, or natural areas
- Is in conformance with any local or regional zoning
- Is in conformance with the "Capability and Development Plan", which provides, among other items, that (1) the proposed development is not to affect significantly a town's ability to provide for a reasonable rate of growth; (2) the development must ensure that its impact on agriculture and forestry potential is minimized; and (3) the proposal must incorporate the best available technology for efficient use of energy.

Permit applications are filed with the appropriate Office of the District Commission or Regional Office of the Vermont Environmental Conservation Agency. After the permit has been issued and construction is complete, the permittee may petition for a Certificate of Compliance, which will foreclose any subsequent legal challenge of the permit issuance.

The relevance of Act 250 to timber harvesting practices need not be overstated. It should be clear that certain such activities may implicate this law and its attendant permit process, and in these cases the developer will need to give the above mentioned environmental assurances.

In contrast to Act 250 and general state land use programs, more specific but less formal procedures have been prepared by the Vermont Department of Forests and Parks to evaluate nonpoint water pollution hazards and to aid in prescribing appropriate erosion control measures. They are included within the "Nonpoint Source Water Pollution Evaluation Handbook - Erosion and Sedimentation".(31) These are field procedures to be used in the forested areas, and they are applicable not only to logging but to most other types of disturbances that might potentially result in erosion and sedimentation. Their emphasis is in determining areas where such disturbances have taken place, the extent of current problems, and the resulting situation if given management practices are not implemented. This document should be consulted along with other appropriate materials so that adverse water quality impacts related to land use practices can be mitigated during timber harvesting.

Water Pollution. Erosion control measures prescribed by the Vermont Department of Forests and Parks, as well as permit procedures pursuant to Act 250, represent important land use controls applicable to timber harvesting in Vermont. At the other end of the process are policies relating to Vermont's water quality and limitations to the amount of material tolerated as stream pollution.

In general, Federal and state water quality policies have been most responsive to pollution emanating from so-called "point" sources such as municipal and industrial dischargers. "Nonpoint" pollution, such as sediment and nutrients in the runoff from a logged-over forest, have not been subject to effluent limitations in any strict or standardized manner.

This has taken place mostly because nonpoint sources are not amenable to structural solutions at the point of discharge. Now that land use practices and controls are becoming increasingly accepted, they are being viewed as the key to the problem of nonpoint pollution. In other words, because sediment and nutrients from the deforested area can not be collected and treated as in a sewage treatment plant, forest managers must institute standards for construction of logging roads and requirements for appropriate buffer strips, so that the creation of high pollutant levels can be averted. In this way, treatment facilities will not be needed.

Regardless of the type of solution to this particular pollution problem, Vermont has adopted standards for the quality of the ambient waters within the state. All waters are classified on the basis of actual or intended use, and standards are assigned according to these designated uses. Vermont's "Regulations Governing Water Classification and Control of Quality", adopted by the Vermont Water Resources Board on December 20, 1973, establish the following classes:(32)

- Class A - suitable for public water supply with disinfection when necessary, character uniformly excellent
- Class B - suitable for bathing and recreation, irrigation and agricultural uses; good fish habitat; good aesthetic value, acceptable for public water supply with filtration disinfection
- Class C - suitable for recreational boating, irrigation of crops not used for consumption without cooking, habitat for wildlife and for common food and game fishes indigenous to the region, and such industrial uses as are consistent with other Class uses.

The State of Vermont has adopted for these classes standards for the following parameters:

- Dissolved oxygen
- Sludge deposits, solid refuse, floating solids, oil, grease, and scum

- Color and turbidity
- Coliform bacteria
- Taste and odor
- pH
- Temperature
- Unspecified other pollutants affecting the composition of bottom fauna, affecting the physical or chemical nature of the bottom, or interfering with the propagation of fish.

Additionally, the state has divided its waters into five management types. Three types are for streams and rivers, and they differ according to the fish populations they might sustain - whether they are warm- or cold-water fisheries, and whether the fish are indigenous or stocked. The other two management types are for lakes, ponds and reservoirs, one being for a natural cold-water fishery, and the second being anything other than that. Separate water quality standards for dissolved oxygen, temperature and turbidity are assigned based on management types.

The ultimate effect of Vermont's water quality standards is that discharges should not cause or contribute to violations of the ambient standards. The emphasis throughout the regulations is on point sources and effluent limitations, but there is no clear statement that nonpoint sources are not meant for control as well. In all cases, state water quality officials should be consulted for their views on the relationship of forestry practices and ambient standards. They can also provide information on designations applicable to specific streams.

Conclusion

It has been shown that timber harvesting can result in water quality impacts. Important, however, is the concept that relatively simple management techniques can mitigate or even eliminate many potentially adverse effects. Adherence to these procedures will allow Vermont to increase benefits from multiple-use lands without sacrificing any options.

State policies in Vermont, moreover, lend weight to the need for effective forestry management, for they are unusually strong in the area of land use controls.

Soil Erosion

Silviculture, the art of producing and tending a forest, necessitates management of a natural resource. One result of this management is soil erosion, the degree and amount of soil erosion depend on the quality of the management. Although soil erosion can result from all aspects of a harvest (roads, skid trails, yarding and staging areas, and the cut surface or harvested area), roads and skid trails have been identified as the major sources of soil loss.(12, 33, 34, 35) Data indicate that tree cutting, even clearcutting, does not change the water handling capacity of a forest soil.(33) Even though the original canopy may be totally removed, the litter cover and forest floor usually remain intact and furnish ample protection until a new canopy is established.(34)

Although roads and skid trails can be identified as the major sources of soil erosion associated with silviculture, magnitude of soil loss is site specific. Each harvest has a potential for soil erosion depending on several factors (slope, road design and maintenance, amount and type of skiding, erosion prevention measures, soil type, etc.). For example, Table 51 shows a summary of studies of the effect of logging on erosion and sedimentation in the United States.(35)

It must be remembered that each example in Table 51 reflects a given set of conditions, thus making comparisons difficult. However, erosion and sedimentation seem to be reported more from roads than from cutting and skiding.(35) A review of the literature on the impact of harvesting on forest environments and resources is presented in reference 36.

Soil erosion, resulting from silvicultural practices, need not be a problem in Vermont. Ample data are available which document preventative measures which can be incorporated into a harvesting plan.(33, 34, 35, 37, 38, 39) In addition, the Vermont Department of Forests and Parks has published criteria which list specifications required for various types of forest

TABLE 51. SUMMARY OF STUDIES OF THE EFFECT OF LOGGING ON EROSION AND SEDIMENTATION IN THE UNITED STATES

Study Location	Accel. Sediment Production		Location & Type Accelerated Erosion				Not Defined	Comments
			Cut + Skid		Roads			
	Yes	No	Surf. eros.	Mass eros.	Surf. eros.	Mass eros.		
N. C.		X					X	Cutting only; no roads, no skidding
Mich.		X					X	
Colo.		X			X			Slight road erosion, no sediment to streams
Wash.		X					X	Sediment not "discernible"
Ore.		X					X	Sediment not "discernible"
Alaska		X		X	X			No significant sediment increase
Ore.							X	Regional, statistical study
Calif.							X	Regional, statistical study
Colo.							X	
Calif.	X							Mostly from channel encroachment
Idaho	X		X		X			Accelerated sed. some drainages, none in others
N. C.	X				X			
W. Va.	X		X		X			Varied with care in logging
Ore.	X		X		X	X		Cut & skid erosion due to slash burning
Ore.	X		X		X	X		
Idaho	X		X		X	X		

Source: 35

roads.(40) The Vermont Department of Forests and Parks also provides the woodlot owner with an example timber sale contract (used when state timber is harvested) which specifies environmental protection measures.(41) Adherence to the aforementioned guidelines should provide satisfactory erosion control for the projected feasibility study.

Effects on Wildlife

The general concern relative to the impacts that could result from timber harvesting operations, and any mitigative measures that might lessen these impacts, is to retain and/or improve the quantity and diversity of wildlife and wildlife habitat that existed prior to these activities. Every habitat must be capable of supplying its inhabitants with certain basic necessities. Food and water in sufficient quality and quantity are obvious requirements for maintenance and reproductive success. In addition, cover is a necessity with a number of implications, including shelter and escape cover from elements and predators, as well as resting and nest protection cover. Added to the above, the habitat must also supply a seemingly endless list of specific individualistic requirements. Thus, the amount, availability, and distribution of food, cover, water, and other special requirements as affected by timber harvesting activities will determine the carrying capacity a particular land unit has for a particular species.

While the word "impact" is normally associated with a negative connotation, it can be positive as well. An activity that is detrimental to one species could conceivably be beneficial to another. For instance, the removal of tall trees would tend to improve the habitat of those species living on or near the ground. On the other hand, such an action would result in the elimination of habitat for those species which occupy the canopy. Thus, forest management practices cannot be wholesalely judged as good or bad for wildlife--only as good or bad for certain species, at certain times, in certain places.

Only rarely would wildlife be directly impacted by timber harvesting or other forest management practices. More typically, such activities directly impact wildlife habitats which, in turn, indirectly impact wildlife.

For example, the removal of vegetation directly impacts the vegetation which indirectly impacts wildlife by changing cover and food supply.

On an individual basis, an alteration in the accustomed composition of the animal's environment, such as produced by a timber harvesting operation, would be expected to lead to either flight from the stress or an attempt to cope with the changed environment. The latter response could conceivably result in a short-term change in behavior which, for example, could affect reproductive success such as abandonment of nesting sites. This behavior would be expected to vary significantly between individuals of a species and is not predictable. On a community basis, however, long-term changes in species composition would be expected to follow the removal of timber or brush. The magnitude of change will depend in large measure on the life form of the disturbed community. The impacts would be greatest in dense forests and brushlands as opposed to more open-type situations.

In general, variety and abundance of wildlife are enhanced in forests that exhibit a variety of age classes and timber types and in which silvicultural operations are active and widely dispersed throughout the forests.(42) The shade of dense old-growth forests is often too great to provide the shrubs and herbs needed for food by birds and animals. A well managed forest with openings can provide abundant supplies. Wildlife also tend to work along the edge areas between the woods and openings since both food and escape cover are readily available.(43) Thus, many forms of wildlife would find the conditions created by timber harvesting operations quite favorable for expansion. For instance, small mammals would be favored by the new growth brought on by increased sunlight. Most seed eating birds would also be favored by the openings created by timber removal as opposed to conditions in deep woods. The openings created in the densely wooded areas would also produce a variety and quality of food for larger animals, such as deer, that would compensate for seasonal deficiencies in surrounding areas.

Today, forestlands occupy some 4.5 million acres of Vermont and account for about 75 percent of Vermont's total land area. Much of Vermont's diverse and abundant wildlife population is of course found in these forested areas.(44) However, most of this woodland is in the pole stage or older categories. The early regeneration or succession stage, which is of prime importance in the wildlife habitat spectrum, is noticeably lacking. As a consequence, much of Vermont's wooded areas have grown beyond the stage where they will support maximum or even minimum wildlife populations.(44, 45) The loss of open lands reportedly has occurred at the rate of 20-25,000 acres per year and has a direct effect on the amount of forest "edge" which is required by all wildlife species.(44) Commercial timber management practices are effective, practical means of slowing the rate of edge loss and thus improving or maintaining this important and productive wildlife habitat.

The quality and quantity of the range utilized by Vermont's whitetail deer herd are of major concern. While less than 10 percent of the total normal annual range serves as the herd's winter range, it is of utmost importance as the deer population cannot survive without suitable wintering areas. The abundance and availability of summer and winter browse is a significant limiting factor for the deer herd. Presently, the deer habitat and browse situation is reported to be in a poor and declining state.(44) This is substantiated by the decline in deer numbers from 250,000 in 1966 to 145,000 in 1973.(46)

In order to remedy this situation, the State Forestry Planning Committee of Vermont has recommended that the intensity of forest management, including thinning and harvest cuts, be greatly increased. Such activities would provide the necessary disturbances to stimulate the low woody growth utilized for browse. In most instances, management of the woodlands for improvement of deer habitat and browse would also be beneficial for other wildlife species common to Vermont, such as black bear, ruffed grouse, woodchuck, and snowshoe hare.(44) The State Forestry Planning Committee, in its statement describing Vermont's forestry situation, has also recommended a number of actions needed to enhance the wildlife potential of the State's forests.(44) Briefly stated, these actions are:

- Integration of wildlife habitat management with forest resource management planning on both private and public land.
- Development of wildlife habitat statistics and potentials along with forest inventories.

- Enlistment of the aid of competent authorities to develop wildlife management guidelines for use by both private and public ownerships.
- Implementation of intensified wildlife management programs on the basis of well designed plans developed cooperatively by professionals.
- Stimulation of the development of markets for timber products so that stands can be economically manipulated to provide the additional benefits of habitat improvement.

Such actions, applied as part of the controlled commercial logging practices discussed elsewhere in this report, will do much to maintain the young productive forest stages that can provide the essential food and cover requirements for wildlife.

Aesthetics

In recent years, public concern with aesthetics and environmental quality has greatly increased, and aesthetic conflicts with an environmentally aroused public are becoming more commonplace. One major focus of this concern is the aesthetic impact of timbers harvesting operations which are penetrating areas previously free from logging activities. Primarily as a result of greater affluence and mobility, more and more people are now able to visit forested areas in pursuit of recreation, scenery, and other environmental amenities, and thus, are coming into more contact with forest management operations. Unfortunately, people traveling through an area may often only be aware of the regional landscape as a sequence of views along a fairly narrow corridor such as a highway. The transiting viewer is thus apt to be very sensitive to the visible presence of timber harvesting operations. Public concern over timber harvesting practices is related primarily to the visual impact; if it looks bad, people automatically assume it is bad. Moreover, as most visitors to an area see it only once, the fact that a cut over area can again be attractive is not visually demonstrated to them.(42) Complicating the program of aesthetic impacts is the fact that an individual's perception of a particular activity such as timber harvesting is largely dependent upon what the individual knows or believes. As a whole, the general public does not possess a specialized knowledge or appreciation of regeneration, working circles, rotations, sustained yields, etc. Thus, their opinion and reaction to timber harvesting operations must be based largely on visual clues. As a result, forest managers are becoming sensitive to appearances and are now modifying harvesting practices to minimize aesthetic impacts. For example, in addition to the size and stage of regrowth, the shape of a cutover area is important. Cutover areas can often be made to harmonize with the general landform by following the lay-of-the-land and/or leaving tree cover in areas, such as saddles and selected portions of clearings. Furthermore, edges which are the interfaces or boundary areas between distinctly different landscape types are especially important and should not suggest disharmony. The visual impact of such edge areas can be lessened by timber harvesting techniques which (1) create small, irregular openings which are similar to natural shapes already present, (2) arrange openings for minimal visibility from likely viewing points, (3) use shelterwood harvesting to create a feathered edge, and 4) cut the boundary or edge area several years ahead of the actual timber harvesting operation.(47) Wagner(47) has recently reviewed the environmental effects of forest management and points out that "... perceiving is not equivalent to seeing" and that "... perception depends on more than the stimulus present and the capabilities of the sense organs. It also varies with the individual's past history and present set or attitude acting through values, needs, memories, moods, social circumstances, and expectations. Thus, what one viewer perceives as desirable land management, another may perceive as aesthetic degradation or even permanent devastation".

While more research is necessary to provide answers to aesthetically-oriented forest management problems, Wagner(47) acknowledges that decisions must be made now and suggests some interim guidelines to be considered with respect to aesthetic values and forest management problems. Briefly highlighted these guidelines are:

1. Where possible, keep logging slash and amenity uses of the forests separate in both space and time.
2. Lengthen rotations in critical view areas to reduce the proportion of a working circle with exposed slash or bare ground.
3. Reduce the scale of slash relative to nearby trees by (a) using partial harvesting methods, (b) leaving islands or clumps of trees within cutting areas, or (c) keeping clearings small.
4. Where clearcutting is practiced, increase the "legibility" of sustained yield forestry by dividing each working circle into a series of "visual" management units.
5. Keep individual clearings small enough that a variety of age classes will fit readily into a visual management unit as mentioned in guideline 4.
6. Where highly productive sites are dedicated primarily to even-aged timber management, create a coarse-textured landscape so that new cuttings and areas of debris remain a part of "ground" rather than becoming "figure".
7. Soften the edges of cutting and slash areas by (a) using irregular shapes, (b) orienting openings for minimal visibility from common viewing points, (c) using partial harvesting systems where practicable, and (d) "feathering" the edges of clearings.
8. Where volumes of debris are small, enhance the appearance of naturalness and hasten rates of decomposition by (a) leaving a residual stand, (b) lopping and scattering, (c) crushing, (d) chipping, (e) piling and burning, or (f) burying.
9. For heavy volumes of debris, create an appearance of "managed concern" by (a) yarding unmerchantable material, (b) windrowing, or (c) piling.
10. Avoid appearances of waste and inefficiency by increasing utilization.

11. Identify and mark "scenic routes" that avoid areas of slash and bare ground along secondary road systems.
12. Relocate trails to avoid unsightly stages of rotations.
13. Create overlooks or short tours that permit a visitor to see all stages of sustained yield timber management--including slash and bare ground--within small area.
14. Use booklets, audio stations, cassette tape tours, short-range radio transmitters (received through visitor's car radio), or other means to help people understand what they are seeing.

In the light of the above, it can be seen that it is in a context of competing values (i.e.--the need for increased forest products and the public's desire for unspoiled, aesthetically pleasing land) that timber management decisions must now be made. Forest management decisions are thus becoming more complex, and few management decisions can be made without damaging someone's interests.

Summary

1. With sound forest management practice, the use of forest surplus as fuel can, on balance, be of benefit to Vermont's ecosystems.
2. Forests remove definable amounts of nutrients from the soil. The rate of removal depends on: (1) species; (2) stocking; (3) age of the stand; (4) available moisture; and (5) soil nutrient availability.
3. The amount of nutrients removed from a site, due to silvicultural practices, varies with the practice and the variables mentioned in one above.
4. The effect of nutrient removal, by harvest, is not known at this time. Available data are site specific and are not amenable to comparisons or projections.
5. Nutrient inputs to forests are variable and are not yet fully quantifiable.
6. Forest fertilization could serve as a source of nutrients. However, fertilization implies good forest management. Due to land-ownership patterns in Vermont, fertilization may

not be feasible on private lands; fertilization would be feasible on state lands.

7. Removing timber from a watershed will result in temporary increases in stream flows depending on the magnitude of cut and reestablishment time of the forest cover.
8. Removal of the streamside canopy will result in increased water temperatures. The magnitude of the temperature fluctuation depends on the length of channel exposed, the volume of water and initial water temperature. Buffer strips, left adjacent to streams, seem to be very effective in maintaining ambient water temperatures within a clearcut area.
9. There is a tendency for nutrient flow, out of the forest soil, to increase following harvest. The magnitude and duration this loss depends on the amount of time between cut and regeneration.
10. Vermont has very effective means of controlling environmentally unacceptable forest harvesting practices, i.e., land use law - Act 250, and regulations governing water classification and control of quality.
11. Soil erosion, associated with silvicultural practices, is due primarily to haul roads and skid trails. Adherence to published guidelines should provide satisfactory erosion control for the projected feasibility study.
12. Much of Vermont's wooded areas have grown beyond the stage where they will support maximum or even minimum wildlife populations. As a result, the Vermont State State Forestry Planning Committee has recommended that timber stands be economically manipulated to provide the additional benefits of habitat improvements.
13. Public concern with timber harvesting practices is related primarily to visual impact.

14. Good management can reduce visual impacts.

Recommendations

1. Environmental impacts resulting from such silvicultural practices as road construction, manipulation of wildlife habitat, visual effects, etc., are well documented. Also, sufficient management techniques are available to diminish or curtail such impacts. It is suggested that the Vermont Department of Forestry and Parks coordinate procurement activities during the projected feasibility study so that accepted silvicultural guidelines are practiced.
2. The effects of residual management on the stability and productivity of forest soils have not yet been resolved. It is suggested that EPA initiate research to address these problems. Such research would involve the following variables:
    - Identification and quantification of nutrient inputs to Vermont's forest soils.
    - Identification and quantification of nutrient outputs from Vermont's forest soils.

However, this nutrient budget must be considered in view of the harvesting techniques and rotation periods projected for wood energy procurement. Such variables as: (1) site(s) potential; (2) species (mixture) selection; (3) rotation projections (species; sites); and (4) amenability to management (ownership, fertilization, etc.) must be considered before selection of the experimental sites can occur.

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APPLICABILITY OF WASTE WOOD FUEL CONCEPT TO OTHER PLANT CAPACITIES AND REGIONS OF THE COUNTRY

The use of wood to fuel electricity generating plants at the 50 MWe level has been shown to be both environmentally sound and cost effective. The question remains as to whether wood fuel must be reserved for small incremental power additions as contemplated in Vermont, or is feasible for larger capacity facilities. More important is whether this rather unique solution to the Vermont energy shortage is site specific or is applicable to other sections of the country.

Applicability to Other Plant Capacities

The waste wood fuel concept envisioned by GMPC calls for the employment of wood as the sole fuel for electricity generating stations. While this concept has been shown both feasible and environmentally and economically attractive, use of wood without supplementing with some conventional fossil fuel places many limitations on the size and economy of this system.

Two major factors will tend to limit the size of any wood-fueled power plant. First, procurement, transportation, and storage problems increase dramatically with increasing plant capacity. Second, because of the variable heat content of the wood chips, only boilers relatively insensitive to these heat content changes such as stoker-fed boilers (maximum capacity approximately 50 MWe) can be employed. Because of the limited capacity per boiler, multiple-boiler plants will be required to achieve increased power rating or a dual firing capability may be required.

In contrast to these limitations on plant size, there are inducements, because of economies of scale, to build boilers as large as possible. Ultimately, the size of any system will be determined by the community requirements and the economic trade-off between procurement system limitations and the economies of scale. Rough estimates, based on transportation distances, suggest that the maximum capacity of any wood-fueled plant will be from 200 to 250 MWe.

Significant increases in capacity, with accompanying economies of scale, are possible through the use of suspension-fired boilers. However, because of the nature of the boiler, the fuel must be of a more consistent heating value than is possible with wood chips alone. The option recommended by many boiler manufacturers is to limit wood firing to 40-50 percent or less of the total fuel content. The remaining fuel can be composed of coal, oil, or gas. Boilers employing combination wood-fossil fuels have been built as large as 175 MWe. The combined fuel concept can be utilized to by-pass even this boiler size limitation. By employing a 10 percent wood - 90 percent fossil fuel combination plant capacities as high as 500 to 1000 MWe would be possible with currently available wood procurement technology.

Applicability to Other Regions

The potential viability of the waste wood for fuel concept can be assessed by comparing the surplus or waste forest biomass available in the different regions of the country with the current fuel requirements for these regions.

Forest Biomass Waste

To facilitate this comparison, an estimate of the wood presently being wasted in current forest harvesting operations and in forest product industries was made. These numbers are rather conservative estimates of the total quantity of wood available for fuel because they include no increase in the cutting of commercial timber, and likely underestimate the quantity of wood available from each category.

Noted below are the three major components of the biomass estimate, along with the method of estimation. In each case the quantity is a fraction of the quantity of commercial timber removed in the year 1970, as reported by the U. S. Forestry Service.*(1)

(1)	Limbs and branches, stumps, and other material normally left in the forest during three harvesting.	50% of Removal
(2)	Harvesting of "Rough and Rotten" old non-prime trees and tree species which are not used in the forest industry (this category includes all timber harvested for stand improvement).	25% of Removal

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* References for this section are given on page 214

(3) Use of forest industry plant wastes such as saw mill residues, and wastes from secondary industry such as furniture manufacture. Also included in this category is waste bark.	20% of Removal

In all cases only that fraction of the material which is currently being wasted, i.e., not used in the pulp and paper or secondary industry, was included to make these estimates.

Regional Fuel Requirements

Recent data on the quantities of fuel utilized in electric power generation in each of nine regions of the United States are presented in Figure 31. Steam-electric utilities consumption of coal, oil, and gas was computed in terms of millions of coal-equivalent tons and plotted versus time, starting in 1964. These numbers are compared in Table 52 (for the year 1970) to the estimated quantity of waste forest biomass, expressed in terms of millions of coal-equivalent tons, to determine those regions where the fuel wood concept might be applicable. As shown in Table 52, the New England, South Atlantic, East South Central, Mountain and Pacific regions all have waste forest biomass totaling from 23 to 103 percent of the electric utility consumption of fossil fuels in the region. Further, in the South Atlantic, Mountain, and Pacific regions the estimated waste forest biomass represents 77, 118, and 103 percent, respectively, of the combined oil and gas consumption by utilities.

Necessary Conditions for Fuel Wood Utilization

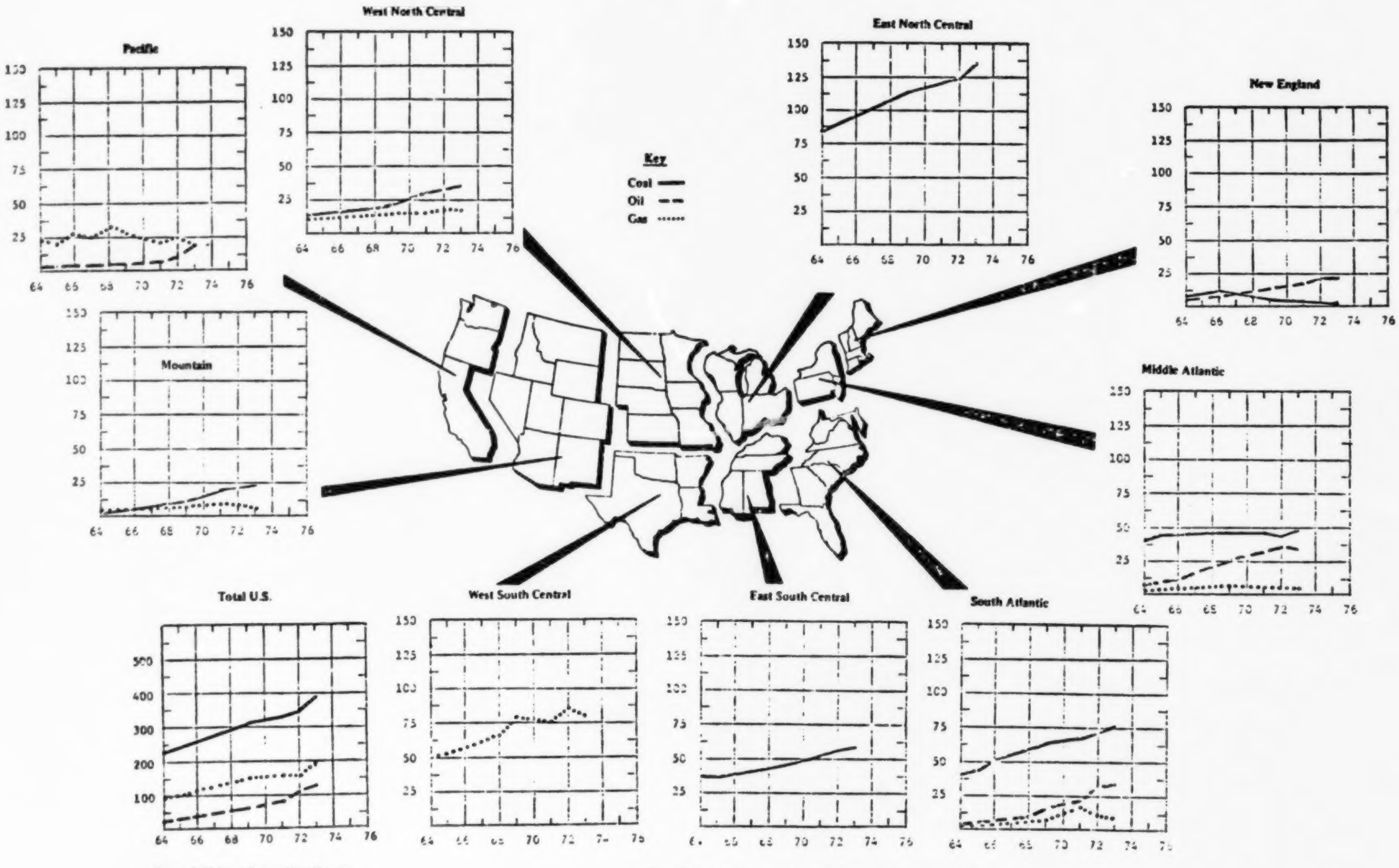
Three conditions are necessary before wood-burning power plants can become a reality:

(1) Supply - An adequate supply of fuel wood must be assured.

(2) Demand - There must be sufficient demand for additional power in the region.

(3) Costs - The cost for electricity from fuel wood must be lower or comparable to that from available fossil fuels.

FIGURE 31. STEAM-ELECTRIC UTILITIES' FUEL CONSUMPTION TRENDS, COAL, OIL AND GAS, BY REGIONS
(Millions of Coal Equivalent Tons)



Source: NCA Steam Electric Plant Factors.

Note: Coal, Oil or Gas are not shown where consumption is relatively small

TABLE 52. COMPARISON OF CONVENTIONAL FUEL USAGE VERSUS QUANTITY OF POTENTIALLY AVAILABLE WASTE WOOD FUEL, BY REGION

Region	Conventional Fuel Usage 10^6 Coal Equivalent Tons(a)				Potentially Available Waste Wood Fuel			
	Coal	Oil	Gas	Total	10^6 cu ft(b)	10^6 Coal Equivalent Tons(c)	Percent of Total	Percent of Oil and Gas
New England	4	15	0	19	534	4.3	23	29
Middle Atlantic	45	30	4	79	341	2.8	4	8
West North Central	25	--	15	40	335	2.7	7	18
East North Central	115	--	--	115	752	6.1	5	--
South Atlantic	65	18	13	96	2,946	23.9	25	77
East South Central	50	--	--	50	1,815	14.7	29	--
West South Central	--	--	76	76	1,762	14.3	19	19
Mountain	14	--	6	20	875	7.1	36	118
Pacific	--	5	25	30	3,818	30.9	103	103

(a) Reference (2). Figures for 1970.

(b) Reference (1). Total volume calculated based on cu ft removed in 1970. The volume was composed of three parts: (1) limbs and branches - 50 percent of removal, (2) rough and rotten - 25 percent of removal, (3) plant residues - 20 percent of removal, including materials from primary, secondary industry normally sent to waste.

(c) Volume of wood converted into equivalent tons of coal based on: (1) density of green chips, 54 lb/ft^3; (2) wood net heating value, 7.8 x 10^6 Btu/ton after correcting for the lower boiler efficiency of wood as compared with coal (9.35 x 10^6 x 0.684/0.820 = 7.8 x 10^6); (3) coal heating value, 26.2 10^6 Btu/ton.

Supply. There appears to be, from the calculations presented in Table 52, at least five regions where the quantity of waste wood is adequate to supply wood-fired power plants. The questions exist, however, whether (1) there exists a sufficient supply of wood within reasonable distance from a proposed power plant site, and (2) there exists sufficient incentive to induce the capital investment required to set up a reliable wood procurement system in the area sufficient to supply a large electric power plant. Only more detailed, site-specific study can determine these facts.

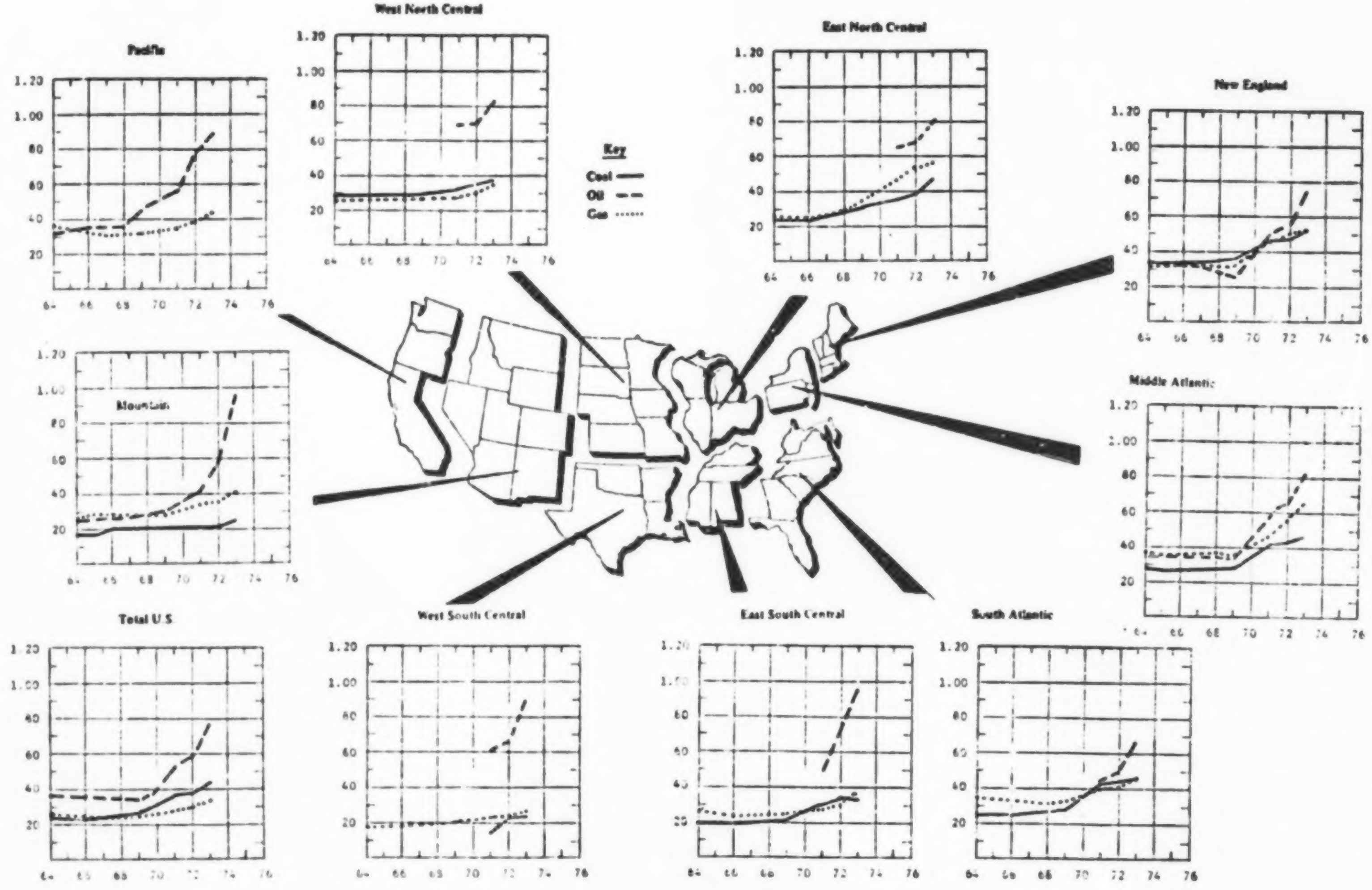
Demand. The demand for electric power, as shown in Figure 31, is on the rise. Various estimates of electric power consumption show that demand has been approximately doubling every ten years. With the depletion of the world's reserves of natural gas and oil, the demand for a clean-burning, replenishable fuel such as wood should be excellent.

According to Federal Power Commission statistics, two of the high wood surplus regions, South Atlantic and East South Central, are near the lowest in reserve electricity capacity of any of the regional electric reliability councils.(3) This low reserve should indicate the need for additional electric generating capacity - capacity that could be, at least partially, supplied by wood fuel.

Costs. The costs for electric power generation are composed of capital costs for construction of the power generation facility, and operating costs comprised mainly of fuel requirements. The capital costs for most fossil fuel plants would be expected to be lower than for a comparable capacity wood fuel plant due to the bulky nature of fuel wood and to boiler size limitations. The capital costs for a plant with a dual capability for firing wood or coal would be somewhat higher than for a plant firing wood alone because of the need for dual fuel handling and storage. Required air pollution control equipment, however, should be less for a wood-fired plant compared to a coal-fired facility.

Fuel costs for fossil fuel vary by region. Data on fossil fuel costs in dollars per million Btu are shown in Figure 32 for nine regions of the United States from 1964 to 1973. While costs are reported only through 1973, the general trend

FIGURE 32. STEAM-ELECTRIC UTILITIES' FUEL COST TRENDS, COAL, OIL AND GAS, BY REGIONS ("As Burned" Cost Per Million Btu)



Source: NCA Steam Electric Plant Factors.

Note: Coal, Oil or Gas are not shown where consumption is relatively small.

of sky-rocketing costs is evident. This trend has increased even more rapidly in the following years. With increases in imported oil costs, deregulation of oil and eventual deregulation of natural gas, fuel costs including coal will continue to rise. While certain areas, such as the low-sulfur coal Western states, will continue to enjoy relatively low-cost fuel most of the country will be forced to pay increasingly high fuel costs. Under this cost climate, waste wood selling at $10-20/ton should be able to compete favorably with fossil fuels for incremental electric power capacity additions.

Conclusions

The following conclusions have been drawn from study of estimates of available waste forest biomass and current and projected levels of energy consumption:

- The use of wood as the sole fuel for electric power generation will limit maximum practical boiler size to approximately 50 MWe. Larger capacity plants must be comprised of relatively expensive, multiple boiler systems or be based on the combined firing of wood and coal.

- The use of combined wood and fossil fuels will allow the use of larger, more cost efficient, suspension-fired boilers. Single boiler capacities of 175 MWe or larger are possible.

- Procurement, transportation, and storage problems may limit the maximum size of any single wood-fired plant to approximately 200-250 MWe. Combined-fuel plants could in theoy be constructed as large as 500-1000 MWe.

- Five of the nine regions of the United States, New England South Atlantic, East South Central, Mountain, and Pacific have waste forest biomass which comprises from 23 to 103 percent of each region's electric utility consumption of fossil fuels. Therefore, the applicability of the waste-wood-for-fuel concept, based on waste wood availability, is multiregional.

- Demand for electric energy is growing steadily, and therefore the opportunity for wood- or wood- and fossil-fuel power plants is excellent.

- The cost of wood compared favorably with other fossil fuels in many sections of the country. Wood's low polluting composition and replenishable supply make wood an attractive alternative to coal, oil, or gas for incremental capacity additions.

- **If a continuous supply of wood fuel cannot be assured, a plant with dual fuel capability must be employed.**

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EVALUATION OF THE USE OF THE MILTON PLANT IN THE PROPOSED DEMONSTRATION

An assessment of the engineering modifications to the Milton Plant required to successfully receive and burn wood fuel, and estimation of the associated costs have been performed under subcontract by the engineering firm of A. E. Stilson, Associates. The effort was intended to be cursory and cost estimates were based on experience, data on-hand, and unit prices of similar equipment. No engineering drawings were prepared to describe the conversion or to assist in the cost estimates. Consequently, considerable additional work will be required to establish the construction details and the cost of the preferred method of adapting the existing plant to burn wood chips. An estimate of these engineering costs is included.

The report from A. E. Stilson, Associates is reproduced in Appendix A. The basic conclusions reached are as follows:

(1) The boilers, turbine-generator, and the plant auxiliaries have been maintained well and seem to be adequate for a few years of service under adequate care and operations.

(2) There are no apparent reasons why the plant cannot be adapted to burn wood chips. However, the physical arrangement of the boilers is not preferred for burning such fuel. The deficiencies and countermeasures which may overcome them are discussed in the report.

(3) Plant modifications are described including the systems required for chip unloading and storage, chip retrieval from storage and conveying into the existing boiler house, chip feeding to the boilers, grate system, combustion air supply, fly ash collection, and ash removal.

(4) The equipment to modify the plant is currently available as standard production items. Delivery may be as long as 1 year for the stokers.

(5) The cost of the modification including engineering is estimated at $680,000.

(6) With regard to the possibility that the planned research program might include the development of design and performance factors relative to burning wood chips to generate steam, the value of data

> which can be obtained is questionable because, as mentioned above, the boiler configuration is not typical of modern design for burning such fuels. If the research is extended into the fields of combustion and pollution control, attention to the boiler deficiencies will be imperative and qualified engineers should play a key role in the entire project.

The following additional comments were made by Battelle engineers and were discussed with a member of the Stilson staff.

> (7) Occurrences of wood-dust explosions have been reported. While the probability of such an explosion is far lower for a system using wood chips rather than sawdust, some fine material is produced during chipping which might accumulate sufficiently to create a problem. Design of the Milton plant modifications and of the projected 50-MW facility should provide safe means for handling wood dust.
>
> (8) A high-vanadium oil should be avoided when burned in combination with wood chips. The potential for ash fouling of the boiler tubes is high for such a combination because of the interaction of the vanadium in the oil and the alkaline components in the wood ash.

Air Quality and Stack Height Consideration

The question which has been raised is whether raising the stack at the Milton Power Plant from 185 ft. to 205 ft. will substantially affect gound level concentrations of particulate resulting from the utilization of wood in the Milton Power Plant boilers. If a mathematical examination of the gound-level concentration equation is performed, it can be shown that the maximum G.L.C. (ground level concentration) decreases 1% for every 1% increase in stack height, for the conditions of zero plume rise, infinite mixing depth, and receptor heights equal to the stack base elevation.

With this formulation, the maximum G.L.C. would decrease by a maximum of 11% by raising the stack 20 ft. This maximum G.L.C. decrease is lessened for cases where there is a plume rise (as is typical with power plants) and also for cases where the mixing depth interferes with dispersion. In most real cases, therefore, the maximum G.L.C. decrease due to increased stack height would be less than 11%.

A computer program was used to verify the above results, and to estimate the expected ground level concentrations. Power plant data provided to the computer program included:

Mixing Depth	1400 meters, an annual (afternoon) average value for Milton
Stack Height	One set of cases at 185 feet, and the other at 205 feet
Stack Diameter	Eight feet
Stack Gas Temperature	550 degrees, allowing for some temperature drop from the stack inlet temperature of 600 degrees
Stack Gas Exit Velocity	We had a value of 3250 cfm. which we first took as 3250 fpm. Later, there was the probability that 3250 represented the 32500 cfm capacity of each of two fans, with a resultant velocity of 1293 fpm. We used both values parametrically noting that the latter value appears more accurate from vis a vis the energy content of the gas stream
Height of Receptor	There is an approximate correction for elevation which we employed to determine the effect of the bluff behind the power plant. Thus, receptor heights of 0 and 200 feet above stack base elevation were examined parametrically.

The results for the most likely combination of parameters, i.e., exit velocity of 1293 fpm, stack height of 185 feet, and receptor height of 200 feet, are plotted as a function of wind speed and stability on Figure 33. The results for a stack height of 205 feet for the smallest and largest wind velocities are superimposed on Figure 33. It is seen that, in general, the effect of increasing stack height by ≤ 20 feet is minimal.

The maximum ground level concentration predicted for each combination of stack height, exist velocity, and receptor height is presented in Figure 34. These results show that maximum G.L.C. is not very sensitive to increased stack height, and somewhat more sensitive to stack gas exit velocity, based upon the Briggs plume rise formulation. The maximum G.L.C. is very sensitive to assumptions of terrain height, but the predicted concentrations for the two terrain heights are expected to bound the actual observed values.

Finally, the actual predicted concentrations can be calculated from the scaled parameters of Figures 33 and 34. Using a wood-heat content of 8 million BTU/ton, a suspended particulate emission factor of 30 lbs/ton wood (EPA AP-42), a heat output rate of 4 megawatts, and a input/output conversion factor of 1 MW = 18 million BTU/hr., it was determined that the heat input rate would be 72 million BTU/hr., requiring 9 tons wood/hr., with a suspended particulate emission of 270 lbs/hr., or 34.0 grams/sec.

The absolute worst case G.L.C. predicted, then, would have a value of 34.0 times 130 (Figure 35), or 4420 ug/m^3 for a short time interval (5-10 minutes). Since weather conditions do not remain invarient, correlations have been drawn to relate maximum concentrations for differing averaging times. In the Ohio River Valley, it has been observed that the maximum 24-hour concentration is approximately 1/8 the maximum 5-minute concentration (Reiquam). Thus, the maximum predicted 24-hour concentration at the Milton plant is 553 ug/m^3, or more than the 24-hour AAQ standard of 260 ug/m^3.

It is furthermore observed that a typical normalized concentration (over all wind speeds and stabilities) in the first two kilometers is 10, corresponding to an actual concentration of 340 ug/m^3. Thus, typical ground level plume centerline concentrations can be expected to create a nuisance in the immediate downwind neighborhood of the plant. Since the prevailing winds at the Milton site are westerly, and residences are proximate to the east side of the plant, control of the emissions is indicated. Nominal 80 percent particulate control would reduce the maximum predicted 24-hour concentration at the Milton plant to 110 ug/m^3, and the typical ground level plume centerline concentration to 68 ug/m^3.

In conclusion, for all of the cases examined (for ranges of the uncertain parameters) it was determined that a 24-hour violation of Federal air quality standards could occur for uncontrolled emissions, and nuisance effects could be expected at the residences near the plant. Raising the stack by 20 feet is not expected to alter these conclusions. Therefore, control of the emitted particulate is indicated.

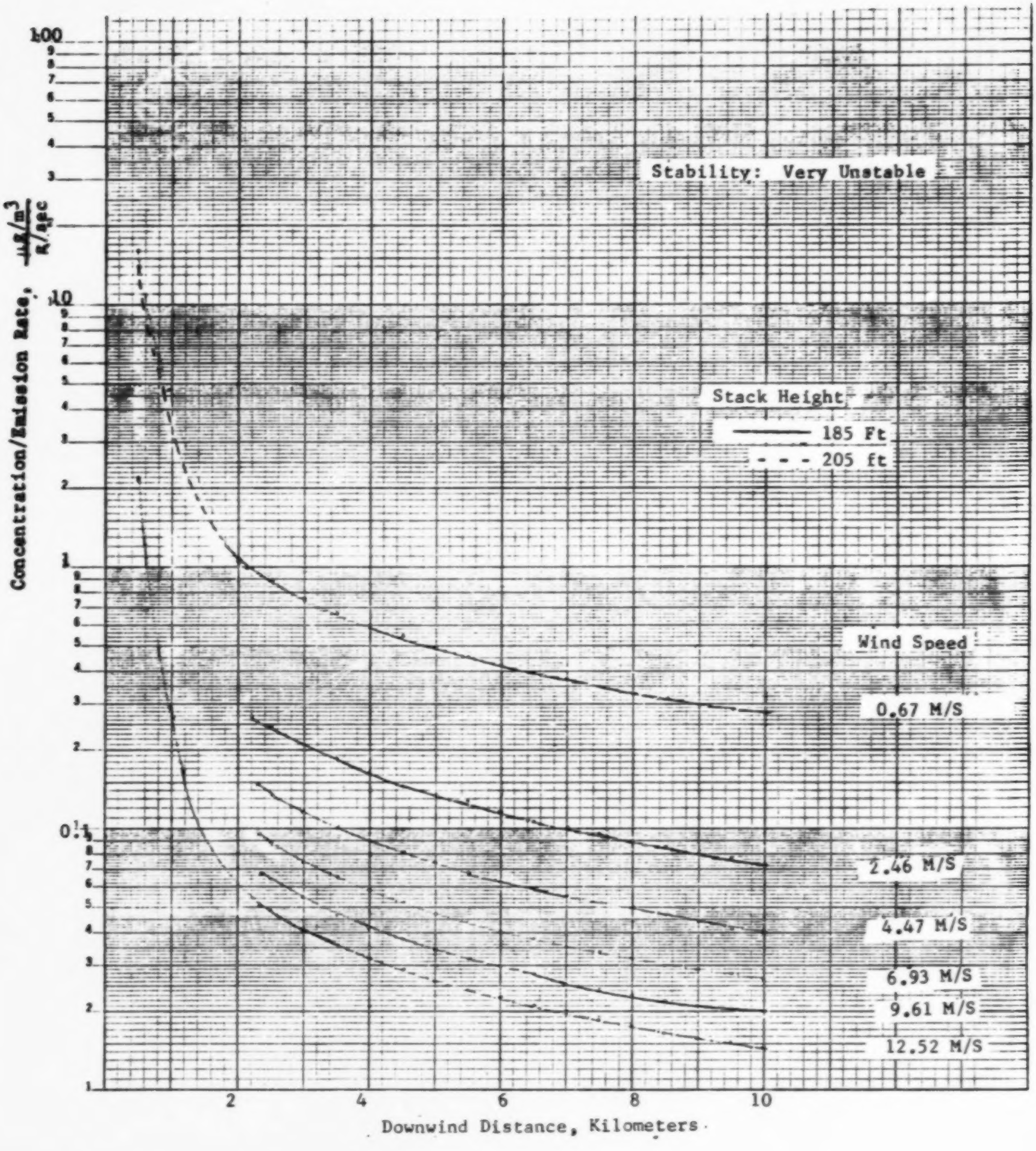

FIGURE 33. GROUND LEVEL CONCENTRATION AS A FUNCTION OF DOWNWIND DISTANCE, WIND SPEED, AND STABILITY

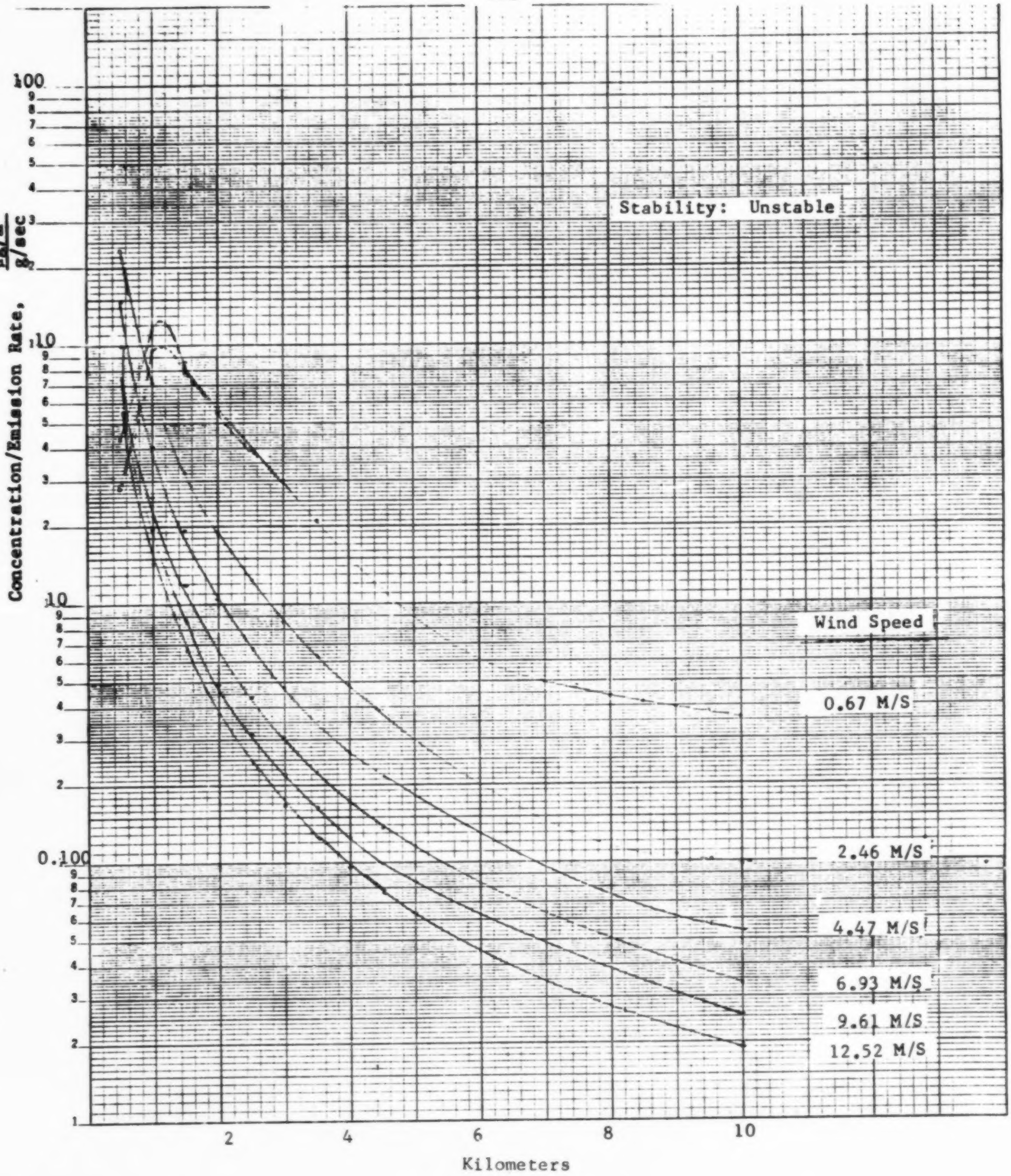

FIGURE 33. Continued

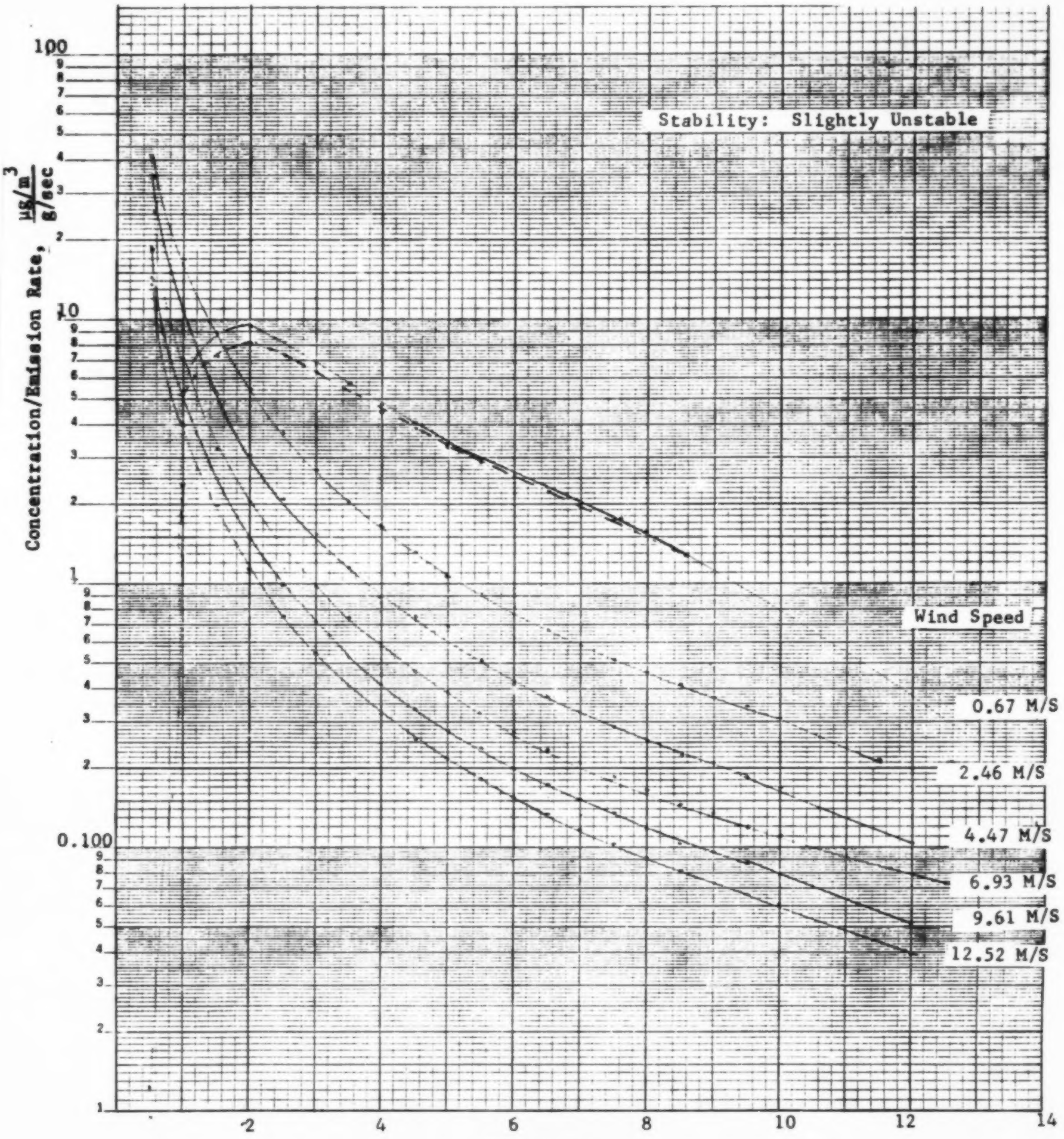

FIGURE 33. Continued

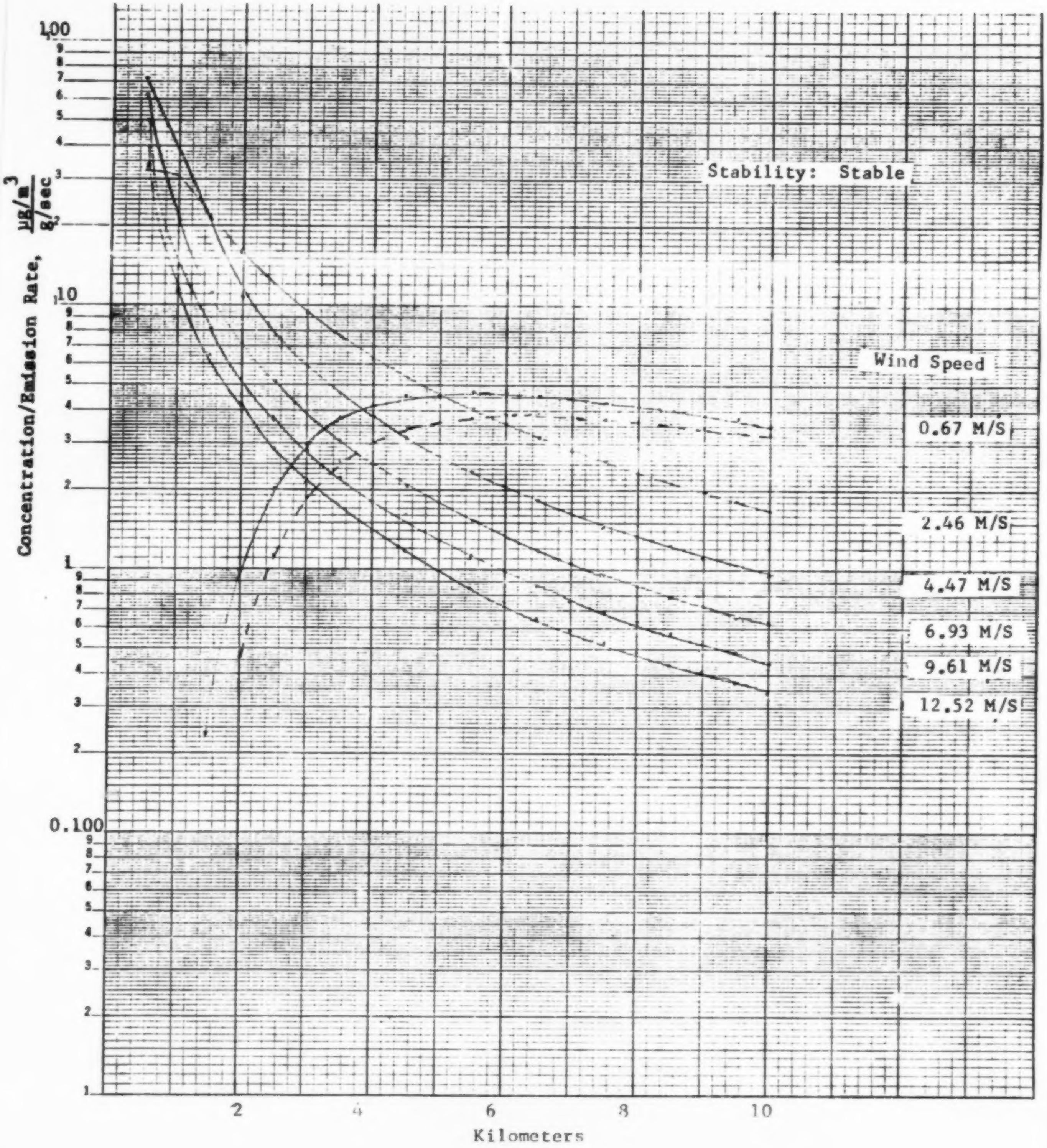

FIGURE 33. CONTINUED

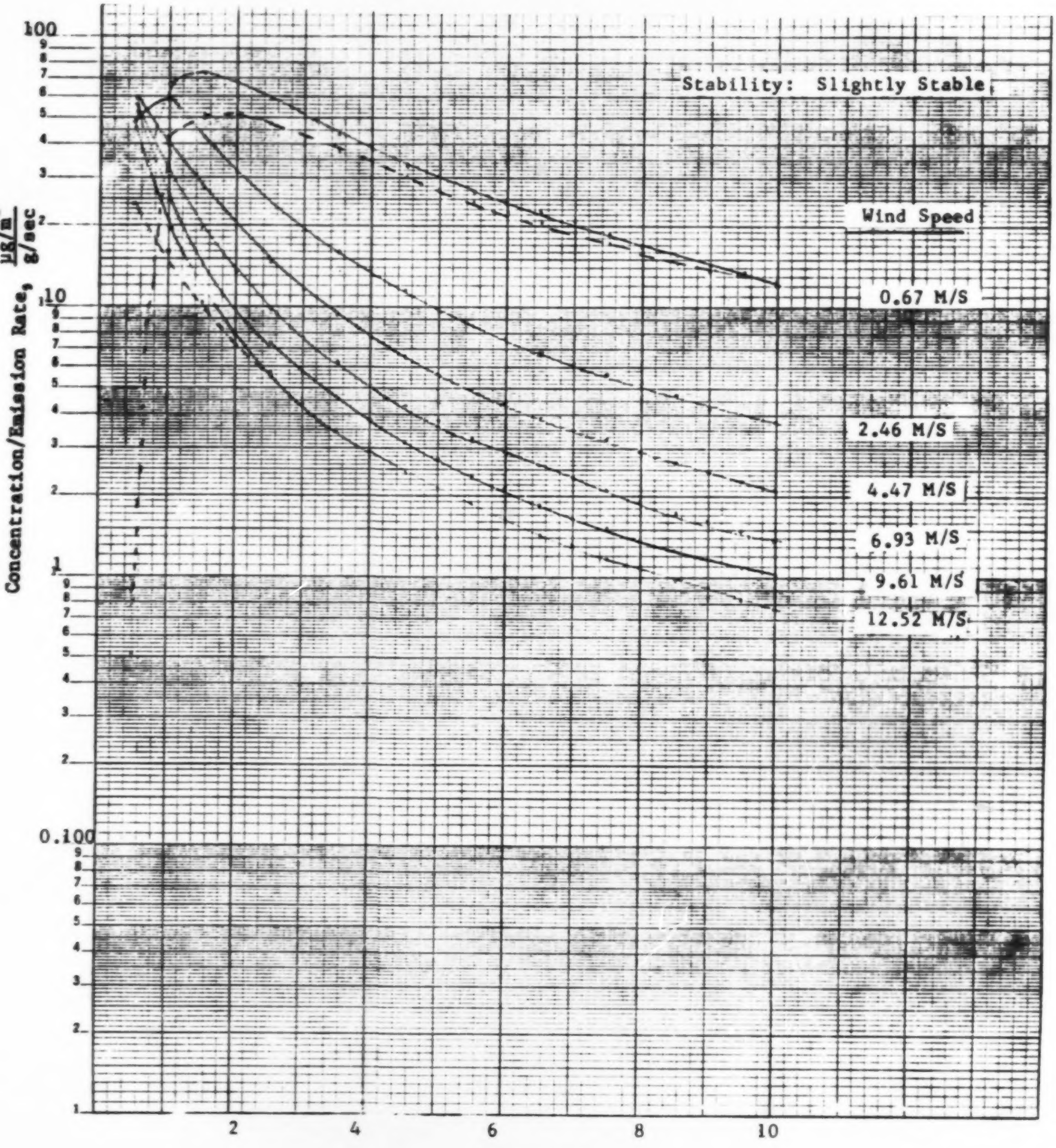

FIGURE 33. CONTINUED

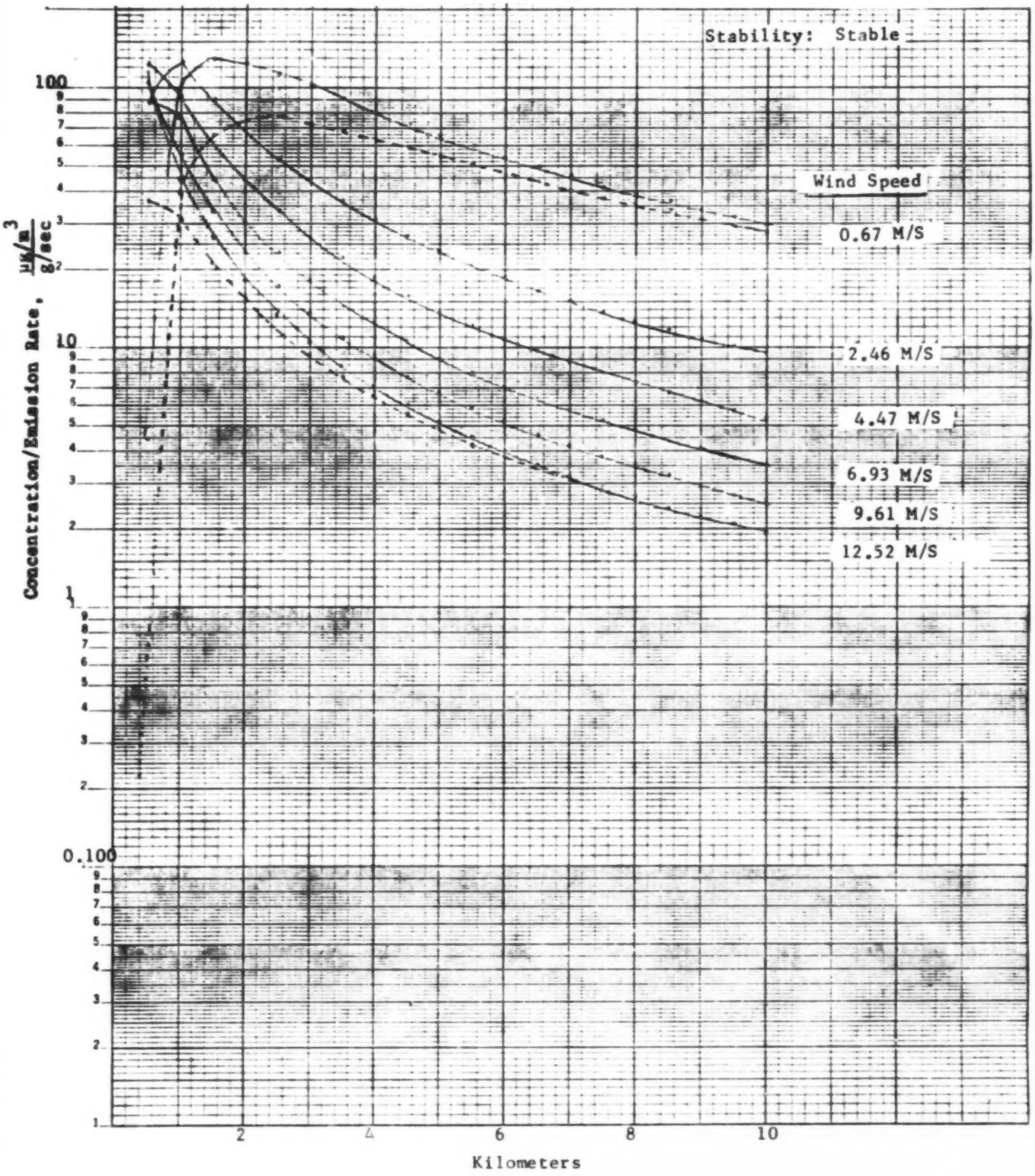

FIGURE 33. CONTINUED

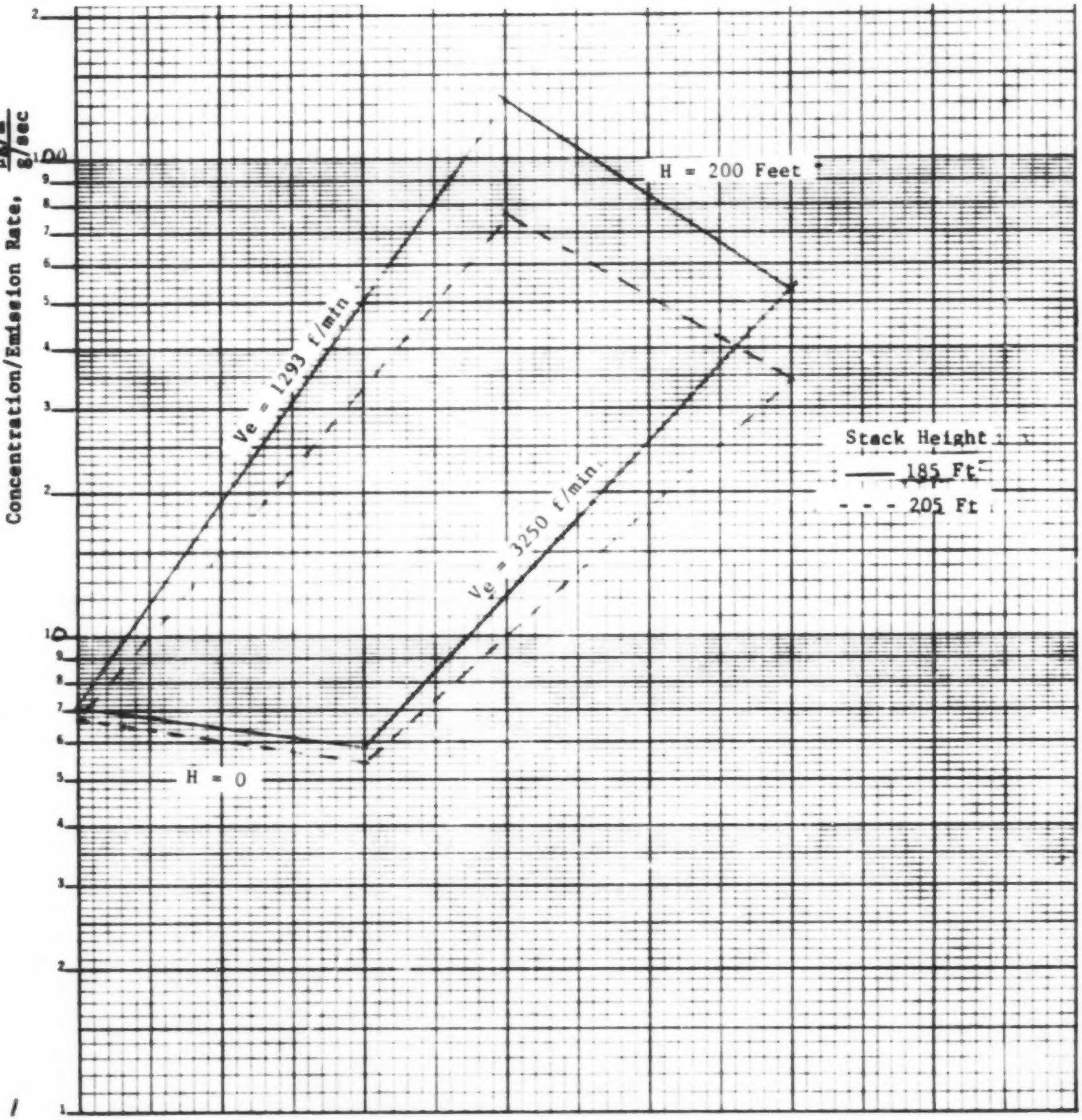

FIGURE 34. GROUND LEVEL CONCENTRATION AS A FUNCTION OF EXHAUST VELOCITY V_e AND TERRAIN HEIGHT H

APPENDIX A

REPORT FROM A. E. STILSON, ASSOCIATES
on
CONVERSION OF THE MILTON PLANT TO BURN WOOD CHIPS

SUMMARY

The results of the study are summarized as follows:

1) The boilers, turbine-generator, and the plant auxiliaries have been maintained well and seem to be adequate for a few years of service under adequate care and operations.

2) The existing oil-fired burners are manually ignited and operated without flame safety equipment. A potential dangerous situation could develop if oil flow were momentarily interrupted during otherwise normal operation.

   It is assumed that the oil burners will be operated at about one fourth their design rate when the wood is burned. Wood chips burning on a grate could provide an ignition source which in turn would tend to reduce the hazard of operating oil burners without flame safety equipment.

   The costs presented in this report do not include adding flame safety equipment to the burners. Several days of study would be required to determine how this could be done and at what cost.

   The legal and liability situations relative to operating safety should be considered in view of not only the well being of the plant operators but also the visitors which will likely be in the plant.

3) There are no apparent reasons why the plant cannot be adapted to burn wood chips. However, the physical arrangement of the boilers is not preferred for burning such fuel. The deficiencies and countermeasures which may overcome them are listed below.

   a) The distance between the chips burning on the grate and the boiler tubes is less than desired. This may be offset by correct application of combustion air and turbulence to avoid flame impingment on the tubes resulting in flame quenching before complete burn out.

   b) The combustion volume is about one half of that normally designed into wood burning boilers. Again, proper proportions and air flow patterns within the flame zone may be adequate to provide acceptable combustion.

SUMMARY
(continued)

c) Superheater surfaces are located on the rear wall of the furnace and away from the flow of the hottest gases from the burning of wood. The use of narrow angle oil burner nozzles and proper setting of the air registers may provide adequate heat over the superheater surfaces. It is assumed that a minimum of one-fourth of the heat input to the boilers will be from oil.

d) The boiler baffles being nearly horizontal provide a few areas where flyash will deposit. Judicial use of adequate soot blowers could likely be affective in avoiding excessive deposits.

The above situations need to be considered during the design of the combustion air supply system. The design should permit adjustment of the air input to achieve adequate combustion.

4) This report describes the plant modifications including the systems required for:

a) Chip unloading and storage

b) Chip retrieval from storage and conveying into the existing boiler house.

c) Chip feeding to the boilers

d) Grate system

e) Combustion air supply

f) Flyash collection

g) Ash removal

5) The equipment to modify the plant is currently available as standard production items. Delivery may be as long as one year for the stokers.

SUMMARY
(continued)

6) The cost of the modification including engineering is estimated at $680,000.

7) Assuming that 75% of the heat to operate the generator at full load, the wood chip burning rate will be approximately 8000 lb per hr per boiler, 16000 lb per hr total.

8) Dr. Beardsley indicated that the planned research program might include the development of design and performance factors relative to burning wood chips to generate steam. The value of data which can be obtained is questionable because, as mentioned above, the boiler configurations is not typical of modern design for burning such fuels. If the research is extended into the fields of combustion and pollution control, attention to the boiler deficiencies will be imperative and qualified engineers should play a key role in the entire project.

CHIP HANDLING AND PLANT MODIFICATIONS

This section discusses the operating conditions and the selection of the equipment and its arrangement to convert the existing boiler plant to burn wood chips. The process starts with chips in a truck delivered to the site and concludes with the flue gas being vented through the existing stack, the discharge of flyash into a container, and the discharge of ash from the boiler stokers into a container.

Operating Conditions

According to the operators of the existing plant burning oil, the turbine generator functions well only when running at nearly the design load of 4 megawatts. This requires the steam from both boilers. Assuming that an equivalent load would be maintained, the operating conditions would be as follows:

1)	Oil rate when burning only oil	720 gal per hr total
2)	Electrical output	4 megawatts
3)	Steam conditions	190 psi, 490F
4)	Heat input	100×10^6 Btu per hr
5)	Plant efficiency	13.7 percent gross
6)	Greenwood characteristics:	Moisture 50 percent Ash 1 percent Heating value 5000 Btu per lb

Operating Conditions (continued)

7) Assume 25 percent of total heat from oil when burning wood chips.
8) Heat input from wood, 75 x 10^6 Btu per hr use 40 x 10^6 Btu per hr to each boiler.
9) Chip feed rate to each boiler, 8000 lb per hr.
10) Grate area in each boiler, 80 sq ft.
11) Burning rate of wood chips, 500,000 Btu per hr per sq ft of grate area. This rate is reasonable.
12) Combustion volume with grates mounted low in the unit; 1600 cu ft.
13) Heat release rate from both oil and wood, 31,250 Btu per hr per cu ft. A rate not exceeding 20,000 is considered good practice.

The heat release rate of 31,250 Btu per hr per cu ft is higher than considered good practice for burning wood. However, good combustions can likely be achieved with good design and control of the combustion air.

Chip Unloading and Storage

The chips would be delivered to the site in closed van semi-type trailers. Standard equipment is available and would be used for unloading the trucks and blowing the chips into a storage pile at the rear of the existing plant. We expect that the nature of the chips would not result in a dust problem to the neighborhood. However, this situation deserves additional consideration.

These chips would be stored outside on the ground, which would require some leveling prior to the beginning of this operation. The chips would serve as its own base for operation on the surface of the ground.

There was some concern that the chips stored in this manner in the open in the winter climates could freeze under some conditions and make the retrieval of the chips for burning difficult if not impossible. However, this was considered improbable by personnel at the Green Mountain Power Company and also by other operators of paper mills who had experience handling wood chips stored outside in temperatures as low as -50F.

Others planning this project considered dumping the chips at the top of the bluff to the east of the plant. From here the chips would be shoved into a chute and by gravity slide into the storage area. In our view, there is not sufficient elevation difference to permit this considering that the storage pile itself would likely be 15 to 30 feet high.

Chip Conveying to the Boiler Room

An operator, using a front end loader, would retrieve the chips from the storage pile and dump them into a mechanical conveyor system to deliver the chips into the boiler house. This system would consist of the following:

1) An operator and a front end loader with a closed cab.
2) Hopper for receiving the chips from the front end loader and distributing them to the conveyor. A vibrating or auger type bottom might be required to meter the chips to the conveyor and to reject or retain any large mass of chips which might be frozen together.
3) Conveyor to carry the chips from the storage area to the exterior of the building at the northwest corner and high above the operating floor. The conveyors and external hoppers for handling the chips should be covered as much as possible, yet permitting easy access for maintenance and operation.
4) Cross conveyor to carry the chips into the boiler house above in front of the boilers. This conveyor would be equipped with a system to unload the chips into a receiving hopper.

Chip Feeding

Chip storage and feeding to each boiler would be provided by the following equipment:

1) Storage bin in front of the boilers and high in the boiler house.
2) An adjustable feed system consisting of dual sets of screws and drives to meter chips independently to each boiler.
3) A swinging spout on each boiler to divide the flow of chips from the feeder into two streams.
4) Gravity chutes to direct the flow to each of two air swept spouts mounted on each boiler. The chips would be introduced at the front of the boiler and below the existing operating floor.
5) Air swept spouts and the fan system to provide air to distribute the chips on the grate.

Chip Feeding (continued)

It would be the operators responsibility to control the feed rate from the storage hoppers into each of the two boilers. The air swept spouts would be adjusted in order to provide adequate distribution of the wood chips on the grate system.

Grates

Each boiler would be equipped with a two-section dump type grate which would be hand operated periodically to discharge the ashes into the ash pits. Using a two-section stoker, only half of the furnace would be cleaned at each time and this would continue to maintain fire in the system.

To provide as much combustion volume as possible in the boiler, the grates would be located as low under the boiler tubes as possible. This will require some modification of the furnace and refractory linings in the lower portion of the new combustion chamber.

Combustion Air Supply

The forced draft fans used for the existing oil burners should continue to be used for this purpose.

For the burning of the wood chips, two additional fans would be installed on each boiler. One fan would supply the under grate air and have a static pressure capability of two inches of water at a flow rate of 7,500 cfm. The other would provide the overfire air for turbulence and the distribution air to spread the wood chips over the grate. This fan would have a pressure rating of 25 inches of water at a flow of 1500 cfm.

The combustion air from all fans would be manually controlled.

Superheat Control

It is anticipated the oil burners on each boiler will have to remain in service and be operated in conjunction with the burning of the wood chips. The oil burners will supply about 25 percent of the required boiler load. They will also provide over fire turbulence for better combustion and by directing the flame at the superheater give superheat control.

Flyash Collection

As a means of particulate emission control, a mechanical dust collector and induced draft fan would be required. The location of this equipment would be exterior to the building in the vicinity of the existing coal silo. Approximately a 100 HP fan would be required. Furnace draft would be manually controlled by adjusting the damper at the fan inlet and the balancing damper at the outlet of each boiler.

The existing breeching would be interrupted at the building wall and replaced with new material up to the inlet of the elevated flyash collector. Flue gas leaving the collector would be ducted to the electric motor driven induced draft fan and thence back to the existing opening in the brick stack.

The mechanical collector would have a bottom hopper for storage of collected flyash material. Dust has burned in hoppers of collectors on bark burning boilers. Therefore, continuous removal of the flyash through a rotary valve is recommended.

The flyash would be discharged to a closed container to be picked up and dumped at an acceptable location.

All of the outside duct work, flyash collector and induced draft fan would be insulated.

Using the above technique 80 to 90 percent of the flyash will be collected. Some steam plume may be visible at the top of the stack during cold weather because of the high moisture in the wood.

Wet scrubber systems were considered undesirable because of the dense steam plume and the tasks of treating and handling the water.

Ash Disposal

Ash from the wood burning would be dumped periodically into the ash pit below the grates. From there they would be hand raked out of the furnace into a container or conveyed out of the building to a receiver. The ash content of wood is about 1 percent, so the quantity of ash to be handled is not large. The ash would be hauled away with the flyash.

Building Modifications

In order to install the stokers the concrete operating floor in front of the boilers would be removed. The stokers would be brought into the building through the windows above the operating floor and then lowered through the new floor openings into the basement area for installation. The concrete work now underneath the front of the boilers would also be removed to receive the stokers, the front stoker plate, and the air swept valves for the chip distribution onto the grate. Metal grating would be reinstalled at the operating floor level and this would give the operator at the floor level a view of the basement area where the air swept valves would be installed.

DESCRIPTION OF THE EXISTING PLANT

The existing power generating station consists of two oil fired boilers and one 4 megawatt General Electric steam turbine generator set. Each boiler is equipped with two atomizing oil fired burners which have been installed in what was originally an underfed coal fired unit. The coal stokers have been removed and refractory floor installed in its place. Each boiler is equipped with a forced draft fan and the flue gas exhausts into a common breeching which is connected to a 135 ft. brick stack.

The boilers are natural circulating water tube type mounted in a brick setting. The tubes and longitudinal-drum are installed inclined to the horizontal with the downtake and uptake headers perpendicular to the tubes and the drum. Gases make three passes, as directed by the refractory baffling arranged parallel with the tubes, before exiting across the drum at the rear of the boiler. The drum is suspended with hangers from overhead columns.

The superheaters consist of ten square tubes mounted horizontally across the rear wall, thus only one side of each tube is exposed to the furnace. The flow is parallel through the tubes and is combined in a header behind and external to the boiler.

Other than boiler water level controls, there are no automatic controls and no flame safety equipment on these boilers. The plant is started by manually igniting a small quantity of No.2 fuel oil which is atomized by compressed air during the warm-up period. As the boiler pressure increases the operators manually admit steam to the turbine and then by increasing the burning rate

DESCRIPTION OF THE EXISTING PLANT
(continued)

and the turbine throttle setting they reach the equilibrium condition for operation.

After the boiler is in operation, the No.6 fuel oil is turned on and steam is used for atomization. The No.6 oil heater is located in the basement in front of the boilers. Throughout the operating period, the fireman operates the boiler maintaining pressure to satisfy the setting of the turbine throttle to provide essentially a constant generator output. The quantity of combustion air is set by the operator using the inlet damper on the forced draft fan.

The stack, approximately 135 feet high, provides the natural draft for the furnace. The fireman adjusts the damper between the boiler and the breeching to maintain the proper negative pressure in the furnace.

The boiler operates at 190 psi and about 490F. Superheat is achieved with surface mounted superheater section at the rear of the boiler. The operator stated that the fuel oil nozzle angle had to be reduced from 90 to 80 degrees to extend the flame further towards the superheater in order to maintain this temperature.

According to the operators, the turbine does not run well unless both boilers are fired and the unit is operated at nearly full load. Under such conditions, the quantity of No.6 oil burned is about 720 gallons per hour and the generator output is 4 megawatts.

The equipment is all in good working order and was fired for a period of about seven hours late in August of 1975. This plant is operated very little and only as needed to maintain the output of the power company.

No water treatment is used for either the make-up water or the boiler water of this plant. According to the operators, it has been on line as much as 30-40% of the time without any detrimental effects due to the lack of water treatment. Make-up water is provided either by the river nearby or the municipal system. Apparently this water is of such quality that treatment is not needed for this boiler which is relatively low pressure for a power boiler.

According to the operators, the soot blowers are working adequately and do provide the means for keeping the boiler surfaces clean. Also, they claim that there was no substantial build-up of flyash on the horizontal baffles even when the unit was firing on coal. The operator did mention that some portion of the soot blower on one unit is not operating well and their attempts to repair this were not successful.

DESCRIPTION OF THE EXISTING PLANT
(continued)

The building is constructed of poured concrete basement, walls and floor; load bearing brick walls; and pre-cast concrete roof supported by steel trusses.

The site is accessible by a good two lane road and there is a stone drive along the north side of the steam plant which appears to be an all weather road suited to handling heavy trucks. There is a bluff 30-50 feet on the east side of the plant which is estimated to be 50-60 feet above the grade of the plant site. A one lane drive at the top of the bluff is used by the oil hauling trucks which discharge oil through a pipeline to the oil tanks below. A stone wall which appeared to be the foundation for some other structure is on the top of this bluff with the foundation remains of coal handling facilities. Others who have been studying the conversion of this plant to burn wood chips have considered unloading the chips on the top of this bluff and then by gravity or mechanical means convey them to storage below.

To the east of the building and north of the brick stack there is a coal silo which has been abandoned. The foundation of this silo could likely be the base for pollution control equipment of the plant converted to burn wood chips.

To the rear, which is south of the existing plant, is an area which could be used for storing the wood chips outside. A few power line poles are located there which might need to be moved. The transformers are located immediately adjacent to the building on the south side. Some protection will likely be required to prevent the tractor operators handling the wood chips from hitting the transformers.

COST ESTIMATES

The cost estimate for the plant modifications is shown below. A more detailed engineering study and design will be required to develop cost estimates of a preferred system. The plant modifications described above mention one mechanical dust collector to be used for flyash control. If greater efficiency in flyash collection would be required, a second mechanical collector could be installed in series with the first and the purchase price of the second collector is reflected by the contingency listed below. The costs are 1975 prices.

Item	Installed Cost for Two Boilers
Chip unloading, storage and retrieval	$ 90,000
Conveyors between the outside chip storage and the hopper in the boiler house	40,000
Storage hopper and chip metering to boilers	60,000
Stokers, including front wall furnace work	130,000
Refractory modifications	40,000
Building modifications	30,000
Induced draft fan and flyash collector	150,000
Electrical	20,000
Engineering	70,000
Contingency	50,000
TOTAL	$680,000

Please let me know if you have any questions regarding this report.

Sincerely,

ALDEN E. STILSON & ASSOCIATES

John D. Hummell

John D. Hummell, P.E.

JDH/mrd
Enclosures